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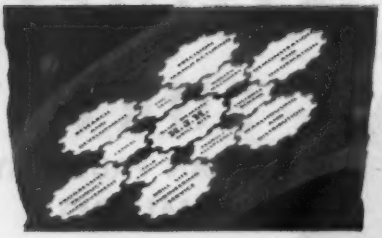

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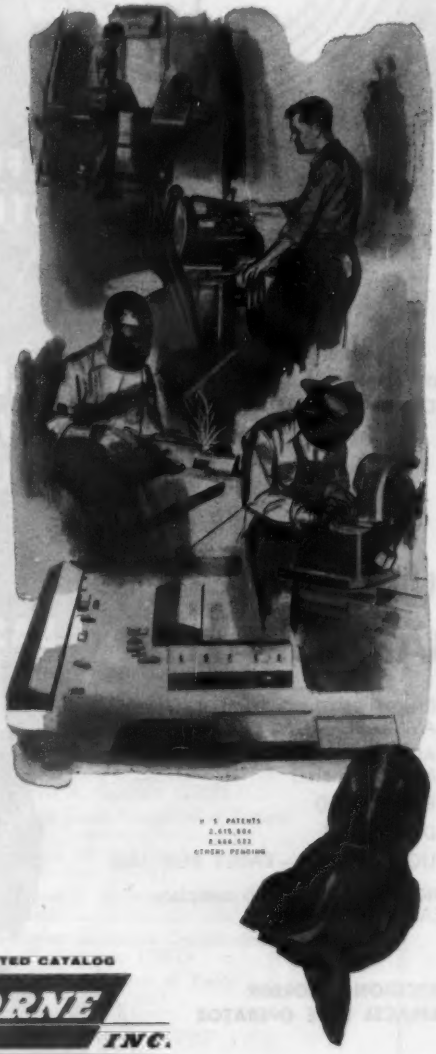

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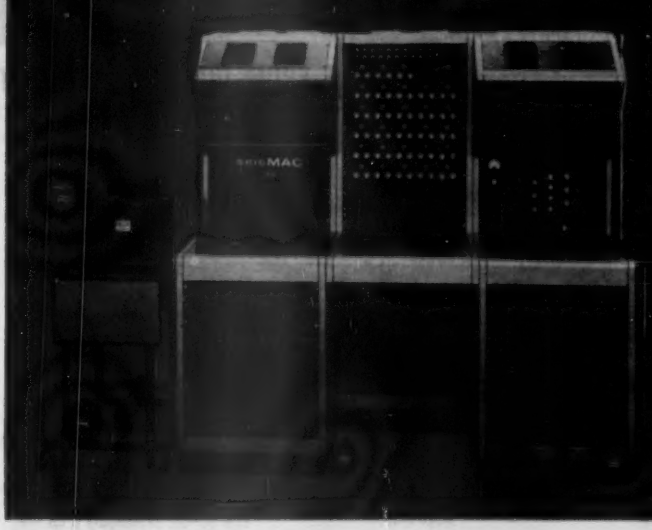

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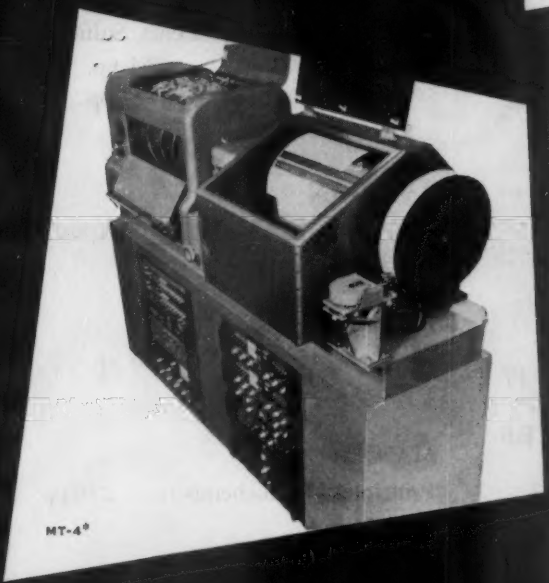

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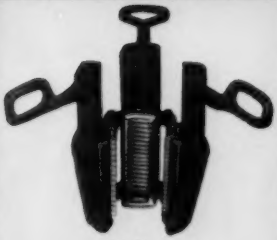

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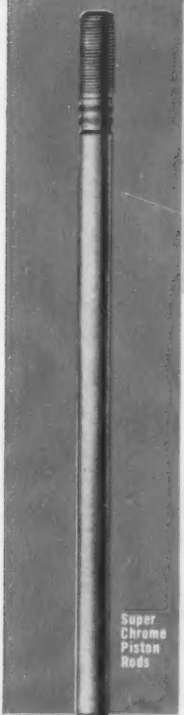

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GEOPHYSICS

PREDICTIVE DECOMPOSITION OF SEISMIC TRACES*

ENDERS A. ROBINSON†

ABSTRACT

The generalized harmonic analysis, or spectral decomposition, of a time series results in its representation in terms of its harmonic, or sinusoidal, components. This paper, on the other hand, develops in an expository manner the generalized regression analysis, or predictive decomposition, of a time series. This decomposition results in the representation of the time series at any moment in terms of its own observable past history plus an unpredictable, random-like innovation.

For the purposes of this paper, it is assumed that a seismic trace (recorded with automatic volume control) is additively composed of many overlapping seismic wavelets which arrive as time progresses. It is assumed that each wavelet has the same stable, one-sided, minimum-phase shape and that the arrival times and strengths of these wavelets may be represented by a time sequence of uncorrelated random variables. By applying the predictive decomposition theorem, it is shown how the wavelet shape may be extracted from the trace, leaving as a residual the strengths of the wavelets at their respective arrival times.

INTRODUCTION

A large part of basic seismic research is directed toward a better understanding of the physical processes involved in the seismic method. Such an approach is fundamentally sound. From this point of view, the seismic trace is the response of the system consisting of the earth and recording apparatus to the impulsive source, the explosion. This system, although usually very complicated, is susceptible to a deterministic (non-statistical) approach toward its analysis. To this end, controlled experiments may be carried out, and mathematical and physical models may be set up from the resulting data. Careful replication of the experiment and high precision of measurement can render such data very accurate. On the other hand, large numbers of seismic records, which have as many as twenty or more traces per record, are needed to carry out an exploration program over a geographic area. This quantity of data necessarily requires the consideration of each record as a member of a larger group or ensemble of records. Thus the reliability of a single record is considerably less than the reliability of the ensemble of records in connection with the description of the geologic conditions existing

* This paper is a condensed version of a thesis submitted on July 26, 1954, in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Massachusetts Institute of Technology. Manuscript originally received by the Editor May 8, 1955. Revised manuscript received by the Editor May 24, 1957.

† Standard Oil Co. (N. J.), 30 Rockefeller Plaza, New York 20, N. Y.

in that area. Also, from an economic standpoint, the amount of control in such an exploration program must be kept at the bare minimum consistent with worth-while results. Thus, as a rule, the controlled experiment aspect of exploration seismology, although possible, falls short of the needs of a research scientist who wishes to set up a mathematical or physical model. As a result, in these cases the working geophysicist must proceed to fit his empirical information into the larger over-all framework without the aid of elaborate mathematical or physical models. Since the geologic structure is physically fixed and constant in nature, and has no intrinsic random characteristics, any statistical approach to this problem immediately encounters difficulties which are commonly associated in the statistical literature with the *Theorem of Thomas Bayes*. Nevertheless, modern statistical theory admits the by-passing of these difficulties, although with reservation, and hence the working geophysicist may be considered to be faced with a situation which is essentially statistical. For example, a reflection which may be followed from trace to trace, record to record, usually has more value to the seismic interpreter and hence is statistically more significant than a reflection which appears only on a few traces. Such a procedure in picking reflections does not imply that the reflection which appears only on a few traces is necessarily spurious information, but only that economic limitations preclude further examination and experimentation which may render it in a more useful form. In the final analysis, the potential usefulness of the statistical approach depends upon the coordination of statistical methods with knowledge of practical and theoretical seismology.

WAVELET THEORY

From a physical point of view, the seismic trace is the response of the system consisting of the earth and recording apparatus to the impulsive source, the explosion. This system, although usually very complicated, is susceptible to a deterministic approach toward its analysis. Nevertheless, the complicated nature of seismograms taken in seismic exploration many times precludes the study of the over-all response of the earth and recording system as a whole. Also, in the final analysis one is interested in the various components of this total response; for example, one wishes to separate components of reflected energy from those of non-reflected energy. In a sequence of fundamental papers, Norman Ricker has proposed and developed the wavelet theory of seismogram structure. A seismogram, according to Ricker, is an elaborate wavelet complex, and the analysis of a seismogram consists in breaking the record down into its components. Ricker (1940) points out that, according to classical theory of the propagation of elastic plane waves in homogeneous, isotropic media, a wave form remains unchanged as it is transmitted. Thus a wave due to a sharp impulse, such as an explosion, should be propagated without change in form and should be received at a distance as the same wave form. Consequently, in media strictly obeying the elastic equations a seismogram should consist of a succession of knife-sharp disturbances due to

waves which have traveled different paths by refractions and reflections. Ricker goes on to state that if such a sharp and clear-cut series of impulses did constitute a seismogram, many of the difficulties in seismic prospecting would disappear. As we know, however, no such simple seismogram is received in the propagation of seismic waves through the earth. Instead he points out that we obtain more complicated seismograms which are familiar to every geophysicist. In order to explain this complicated nature of a seismogram, Ricker proposes his wavelet theory of seismogram structure. The reader is referred to Ricker's work in which he demonstrates mathematically and experimentally that a sharp seismic disturbance, or impulse, gives rise to a traveling wavelet, the shape of which is determined by the nature of the absorption spectrum of the earth for elastic waves. The shape of this wavelet, which is a time function, is the response of the earth to the sharp seismic disturbance, or impulse. A seismogram, then, consists of many of these wavelets, with different strengths and arrival times, due to disturbances which have traveled different paths by refractions and reflections.

Thus the seismogram may be visualized as the totality of transient responses to sharp impulses, each sharp impulse being associated with a disturbance which has traveled a certain path by refractions and reflections. These transient responses, or response functions, are the seismic wavelets or Ricker wavelets. The analysis of a seismogram consists in breaking down this elaborate wavelet complex into its component wavelets. In particular we desire the arrival times of the theoretical sharp impulses which produce these wavelets or responses. There are two basic approaches which one may use toward the solution of this problem, the deterministic approach and the probabilistic or statistical approach. In the deterministic approach one utilizes basic physical laws, for example, in order to determine the shape of the wavelet or the absorption spectrum of the earth. At all stages in such an investigation one may compare mathematical results with direct and indirect observation of the physical phenomenon. In this paper we are concerned with the statistical approach. Such an approach in no way conflicts with the deterministic approach, although each approach has certain advantages and disadvantages which do not necessarily coincide. In practice the two approaches may be utilized in such a manner so as to complement each other.

STATISTICAL APPROACH

Let us apply the probabilistic approach to one specific problem which, as we shall see, is a problem treated by Wadsworth, et al (1953). Let us set up a hypothetical situation. Let us assume that a given section of seismic trace is additively composed of Ricker wavelets, where each wavelet has the same shape or form. We shall assume that the shape of the wavelet is given by a realizable, stable, minimum-phase time function. Hence each wavelet is a one-sided transient which damps with a certain degree of rapidity. Further, we assume that from knowledge of the arrival time of one wavelet we cannot predict the arrival time of another wavelet; and we assume that from knowledge of the strength of one wavelet we

cannot predict the strength of another wavelet. Finally, let us assume that the seismic trace is an automatic volume control (AVC) recording so that the seismic trace has a constant standard deviation (or variance) with time. The specific problem which we wish to consider is the following: given the seismic trace described in this paragraph, determine the arrival times and strengths of the Ricker wavelets and determine the basic wavelet shape. We shall discuss a theoretical solution of this problem and shall also discuss a practical solution which involves statistical estimation.

Let us translate our assumptions about the seismic trace into mathematical notation for discrete time t. First we let the discrete time function b_t represent the ordinates of the fundamental Ricker wavelet at discrete, equally-spaced, times t. Our assumption about the nature of this wavelet is that the b_t are the coefficients of a realizable, stable, minimum-phase linear operator. In other words, we assume that $b_t = 0$ for t less than zero so that the wavelet is one-sided, and that

$$\sum_{t=0}^{\infty} b_t^2 < \infty; \qquad \sum_{t=0}^{\infty} b_t z^t \neq 0, \qquad |z| < 1, \tag{1}$$

hold so that the wavelet is a damped, minimum-phase time function. Let the strength, or weighting factor, of the wavelet which arrives at time t be given by ϵ_t. Thus at time t, this wavelet has ordinate $b_0\epsilon_t$; at time $t+1$, it has ordinate $\epsilon_t b_1$; at time $t+2$, it has ordinate $\epsilon_t b_2$; and so forth. The variable ϵ_t is the theoretical knife-sharp impulse of which the particular wavelet (i.e., the one which arrives at time t) is the response. For example, if no wavelet arrives at a particular time t, then $\epsilon_t = 0$.

In our discussion of the nature of the seismic trace, we shall call the knife-sharp impulses ϵ_t "random variables." Our use of the term "random variable ϵ_t" does not imply that the variable ϵ_t is one whose value is uncertain and can be determined by a "chance" experiment. That is, the variable ϵ_t is not random in the sense of the frequency interpretation of probability but is fixed by the geologic structure. Frechet describes this type of variable as "nombre certain" and "function certaine" and Neyman translates these terms by "sure number" and "sure function." Another example of a "sure number" is the ten-thousandth digit of the expansion $\pi = 3.1415926 \cdots$, which, although unknown, is a definite fixed number. Since the knowledge of the working geophysicist about the entire deterministic setting is far from complete, we shall treat this incomplete knowledge from a statistical point of view. We thus call ϵ_t a "random variable," although we keep in mind that it is a "sure number."

Our assumption about the unpredictability of the arrival times and strengths of wavelets means mathematically that the knife-sharp impulses ϵ_t are mutually uncorrelated random variables; that is, $E(\epsilon_t \epsilon_s) = E(\epsilon_t)E(\epsilon_s)$ for t not equal to s. Our assumption that the knife-sharp impulses ϵ_t are mutually uncorrelated with each other is an orthogonality assumption and is a weaker assumption than the assumption that the ϵ_t are statistically independent, which we need not make.

Returning again for the moment to our discussion about the "sure" nature of the knife-sharp impulses ϵ_t, we see that the assumption that they are mutually uncorrelated does not hold in a completely deterministic system. Nevertheless, such an assumption is a reasonable one for the working geophysicist whose knowledge of the entire deterministic setting is far from complete and who is faced with essentially a statistical problem. In other words, we assume that knowledge of the arrival time and strength of one wavelet does not allow us to predict the arrival time and strength of any other wavelets. In particular, we assume that an arrival time and magnitude of a reflection from a certain reflecting horizon does not allow us to predict the arrival time and magnitude of a reflection from another reflecting horizon.

PREDICTIVE DECOMPOSITION

We have assumed that our seismogram trace is additively composed of wavelets, all with the same shape b_s, but weighted by their respective strengths ϵ_t. That is, at the time t, the wavelet which arrives then gives the contribution $\epsilon_t b_0$; the wavelet which arrived at $t-1$ gives the contribution $\epsilon_{t-1}b_1$; the wavelet which arrived at $t-2$ gives the contribution $\epsilon_{t-2}b_2$; and so forth. The seismic trace x_t at time t then is the summation of all these contributions, and hence we may write this wavelet complex mathematically as

$$x_t = b_0\epsilon_t + b_1\epsilon_{t-1} + b_2\epsilon_{t-2} + \cdots = \sum_{s=0}^{\infty} b_s\epsilon_{t-s} \tag{2}$$

for the time interval (t_1, t_2), called the operator time interval, which comprises our basic section of seismic trace. This equation includes tails of wavelets with shape b_t, these wavelets being due to knife-sharp impulses ϵ_{t_1-1}, ϵ_{t_1-2}, $\cdots$ which occur before time t_1. Without loss of generality, we may center the knife-sharp impulses ϵ_t so that their mean $E(\epsilon_t)$ is equal to zero. Our assumption that the seismic trace have constant variance; that is, that $E(x_t^2)$ be constant, means that the strengths ϵ_t of the impulses must have constant variance; that is $E(\epsilon_t^2)$ must be constant, which without loss of generality we shall take to be unity. Thus the ϵ_t represent an orthonormal sequence of random variables. For the purposes of our theoretical discussion, let us assume that our assumptions about the time series x_t, equation (2), now hold for all time. Thus equation (2) becomes the mathematical representation of the *Predictive Decomposition Theorem of Wold* (1938) for a purely non-deterministic stationary time series.

In equation (2) the wavelet shape b_t represents the "dynamics" of the time series, whereas the impulses ϵ_t represent the "random" nature of the time series. Our problem then consists of the extraction of the wavelet shape b_s from the trace x_t so as to yield the impulses ϵ_t which represent the wavelet strengths at their respective arrival times t. The theoretical procedure for infinite time series is as follows.

First, we wish to average the random components ϵ_t out of the time series x_t

so as to yield the wavelet shape b_t. In order to do so, we may use the following procedure. From the realization of the time series $x_t(-\infty < t < \infty)$ compute the autocorrelation function $\phi(\tau)$. Then take the Fourier transform of the autocorrelation to yield the power spectrum $\Phi(\omega)$. Next factor the power spectrum into $\Phi(\omega) = B(\omega)B(-\omega)$ where the Wold-Kolmogorov factor $B(\omega)$ is required to have no singularities or zeros in the lower half plane. If $\Phi(\omega)$ is a rational function, we use Wold's method of factorization; otherwise, we use Kolmogorov's method. The W-K factor $B(\omega)$ is the complex phase and amplitude spectrum of the desired wavelet b_t, and so we find b_t from $B(\omega)$ by the Fourier transform

$$b_t = \frac{1}{2\pi}\int_{-\pi}^{\pi} B(\omega)e^{i\omega t}d\omega. \tag{3}$$

Let us now examine this procedure in more detail. The computation of the autocorrelation function averages out the random, uncorrelated elements ϵ_t and preserves the dynamic wavelet shape b_t in the form of the autocorrelation of the wavelet shape. In other words, the autocorrelation $\phi(\tau)$ of the time series x_t is the same function as the autocorrelation of the wavelet b_t. In the computation of the power spectrum $\Phi(\omega)$ we are, in effect, computing the energy spectrum $|B(\omega)|^2$ of the wavelet since the power spectrum $\Phi(\omega)$ of the time series is the same function as the energy spectrum of the wavelet b_t. Since the absolute frequency spectrum $|B(\omega)|$ is the real positive square root of the energy spectrum $|B(\omega)|^2$, we may immediately find $|B(\omega)|$ which is equal to $\sqrt{\Phi(\omega)}$. Now there are many different wavelet shapes which have this same absolute frequency spectrum $|B(\omega)|$ but with different phase spectra. Nevertheless, only one of these wavelet shapes is a realizable, stable, minimum-phase transient time function; the complex phase and amplitude spectrum of this unique wavelet shape is the W-K factor $B(\omega)$. Since we have assumed that our hypothetical wavelet is a realizable, stable, minimum-phase function, it follows that the W-K factor $B(\omega)$ must be the complex phase and amplitude spectrum of our wavelet. The W-K factor $B(\omega)$ is equal to $\sqrt{\Phi(\omega)}\exp i\theta(\omega)$ where the minimum phase characteristic $\theta(\omega)$ is given by

$$\theta(\omega) = -\frac{1}{\pi}\sum_{t=1}^{\infty}\sin \omega t \int_0^{\pi}\cos ut \log \Phi(u)du. \tag{4}$$

Hence the wavelet b_t may be found from $B(\omega)$ by means of equation (3).

Next, using the wavelet shape b_t thus found, we wish to remove this wavelet shape from x_t, thereby leaving, as a residual, the random components ϵ_t. In order to do so, we use the following procedure. From the wavelet shape b_t, we find the inverse wavelet shape a_t by means of

$$a_0b_0 = 1, \qquad \sum_{s=0}^{n} a_sb_{n-s} = 0, \qquad n = 1, 2, 3, \cdots. \tag{5}$$

We now use the inverse wavelet shape a_t to remove the wavelets, all of which are of shape b_t, from the time series x_t by means of the linear operation

$$\sum_{s=0}^{\infty} a_s x_{t-s} = \sum_{s=0}^{\infty} a_s \sum_{r=0}^{\infty} b_r \epsilon_{t-r-s} = \epsilon_t. \tag{6}$$

In other words, the operator a_s acting on the time series x_t yields the knife-sharp impulses ϵ_t. Furthermore, the Wold decomposition theorem tells us that the inverse wavelet shape a_t is the optimum least-squares prediction operator, and the $b_0\epsilon_t$ are the prediction errors for unit prediction distance.

Thus by these theoretical steps we may separate the dynamic component, represented by the transient response function or wavelet shape b_t, from the random component, represented by the knife-sharp impulses ϵ_t which represent the strengths of the wavelets at their respective arrival times.

FILTERING

To filter the seismic trace in the sense of separating message and noise, one further step is added. This step consists of reaveraging the prediction errors ϵ_t by means of a stable linear operator q_t which is determined from the spectra and cross-spectra of message m_t and noise n_t, where $x_t = m_t + n_t$.

Let $\Phi(\omega)$ be the power spectrum of x_t, $\Phi_{11}(\omega)$ be the power spectrum of the message, and $\Phi_{12}(\omega)$ be the cross-spectrum of message and noise. As before, let $B(\omega)$ be the W-K factor of $\Phi(\omega)$, b_t be the realizable, stable, minimum-phase operator obtained from the W-K factor $B(\omega)$, and a_t be the inverse, realizable, stable, minimum-phase operator with transfer function $A(\omega) = 1/B(\omega)$. The operator a_t is obtained from b_t by means of equation (5). The q_t is then given by

$$q_t = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{\Phi_{11}(\omega) + \Phi_{21}(\omega)}{B(-\omega)} e^{i\omega t} d\omega. \tag{7}$$

and the optimum estimate of the message at time $t+\alpha$ in the sense of the principle of least squares is

$$\hat{m}_{t+\alpha} = \sum_{s=0}^{\infty} q_{s+\alpha} \epsilon_{t-s}. \tag{8}$$

Using equation (6), this expression becomes

$$\hat{m}_{t+\alpha} = \sum_{r=0}^{\infty} h_r x_{t-r} \tag{9}$$

where the operator coefficients h_r are given by

$$h_r = \sum_{s=0}^{\infty} q_{s+\alpha} a_{r-s}. \tag{10}$$

WAVELET CONTRACTION

Doob (1953) considers the case in which the time series is made up of wavelets, all with the same realizable, stable shape c_s which is not minimum-phase. That is, the time series x_t may be written

$$x_t = \sum_{s=0}^{\infty} c_s \xi_{t-s}, \qquad \sum_{s=0}^{\infty} c_s^2 < \infty, \qquad E(\xi_t^2) = 1, \qquad E(\xi_j \xi_k) = 0, \qquad j \neq k. \tag{11}$$

By shifting subscripts if necessary, we see that it is no restriction to assume $c_0 > 0$. Doob (1953) shows that this time series is stationary and purely non-deterministic. Since c_s is not a minimum-phase operator (i.e., we assume that c_s violates the minimum phase condition (1)), there will be a uniquely determined different operator b_s which is minimum-phase and a different orthonormal sequence ϵ_t, so that the decomposition (2) holds for x_t. That is, the operator b_s is the one determined by the W-K factorization of the spectrum, and the ϵ_t are the associated orthonormal prediction errors. We note that the wavelets b_s and c_s each have the same absolute gain. Moreover, Doob shows that b_0 must always be greater than c_0. Thus if the wavelet shape $c_s (c_0 > 0)$ violates condition (1), there will be no realizable, stable, inverse operator which will contract the wavelet c_s into a knife-sharp impulse. Accordingly, we may only be able to contract the wavelet to one of lesser breadth, and once again we see the tie-in with the fundamental work of Ricker (1953) on wavelet contraction.

STATISTICAL ESTIMATION

The practical solution of the problem of separating the "dynamic" and "random" components of a finite section of seismic trace involves statistical estimation. One method consists of estimating the prediction operator, or inverse wavelet shape, directly from the finite section of seismic trace. For this purpose one may use the Gauss method of least squares as described in Wadsworth, et al (1953). Since the method described there is more general, let us write down the equations to be used for our specific problem in which we consider only one trace x_t for a prediction distance equal to one. Let us note these differences in notation: the prediction distance k of Wadsworth, et al (1953) is our α; the operator coefficients $a_s (s = 0, 1, \cdots, M)$ of Wadsworth, et al, are respectively our operator coefficients $k_s (s = 0, 1, \cdots M)$; and the operator coefficients b_s for the y-trace of Wadsworth, et al, are not our operator coefficients b_s in this paper. In other words, our use of the symbols a_s and b_s is different from the use of the symbols a_s and b_s in Wadsworth, et al (1953). Then utilizing our notation, equation (37) of Wadsworth, et al, (1953) becomes for the special case of our problem:

$$\hat{x}_{t+1} = c + \sum_{s=0}^{M} k_s x_{t-s} \tag{12}$$

where we use the same notation except for the differences we have just noted. Ac-

cording to our convention, we have let the spacing $h=1$, so that the running index t is the same as the running index i. We note that a constant c appears in equation (12) to take account of the mean value of the time series, since now we do not require the mean to be zero. The operator time interval (Wadsworth, et al, 1953) is chosen to be the time interval of the section of trace which we assume to be a section of a stationary time series. The solution of the normal equations (40) of Wadsworth, et al, (1953) then yields the operator coefficients c, k_0, k_1, $\cdots$, k_M. Since the prediction error for unit prediction distance is given by $b_0\epsilon_t=x_t-\hat{x}_t$, we see that by comparing the prediction operators (6) and (12) their operator coefficients are related by $a_0=b_0^{-1}$, $a_1=-a_0k_0$, $a_2=-a_0k_1$, $\cdots$, $a_m=-a_0k_M$, and $a_s=0$ for s greater than m, where $m=M+1$. This relation allows us to determine immediately the inverse wavelet shape a_t from the solution k_t of the normal equations since for convenience we may let $a_0=b_0=1$, at the expense of the ϵ_t no longer having unit variance. The constant c of equation (12), which adjusts for the mean value of the empirical trace, is not used in determining the shape a_t of the wavelet. Provided that a_t is a minimum-phase operator, the shape b_t of the Ricker wavelet may be readily computed from a_t by means of equation (5). In terms of the prediction operator k_s of equation (12), we have $b_t=0$ for t less than zero, $b_0=a_0^{-1}$, and

$$b_{t+1}=-a_0^{-1}\sum_{s=1}^{m}a_sb_{t+1-s}=\sum_{s=0}^{M}k_sb_{t-s},\qquad t=0,1,2,\cdots. \tag{13}$$

That is, the dynamic wavelet shape b_t for $t>0$ is determined by successive step-by-step predictions from its past values, where we let the initial values be $b_t=0$ for $t<0$ and $b_0=a_0^{-1}$.

As we have seen, the Gauss method of least squares described yields an empirical estimate of the theoretical prediction operator or inverse wavelet shape. This empirical estimate has certain optimum statistical properties under general conditions. For a treatment of the optimum properties of linear least-squares estimates, see Wold (1953). Provided that trace in the operator time interval is approximately stationary, a good estimate of the prediction operator should yield prediction errors within the operator time interval which are not significantly autocorrelated. In other words, the prediction errors ϵ_t within the operator time interval should be mutually uncorrelated at some preassigned level of significance. In Figure 1, in the left-hand diagram, we show the prediction operator a_s computed by the Gauss method for trace N650 for the operator time interval 0.350 second to 0.475 second on MIT Record No. 1 (supplied by the Magnolia Petroleum Company). This seismogram is illustrated and described in Wadsworth, et al (1953). In the right-hand diagram of Figure 1, we show the inverse prediction operator, which is the shape of the Ricker wavelet b_t. The shape of the Ricker wavelet was "predicted" by means of equation (13). In these computations, we used discrete time series where the spacing $h=2.5$ milliseconds. In plotting a_s and b_t we followed our usual procedure which is to plot discrete time

functions, such as a_s and b_t, as discrete points and then to draw a smooth curve through these discrete points. We note that the prediction operator a_s is plotted in the reverse manner, as described by Swartz and Sokoloff (1954); that is, the time lag s runs in the positive direction toward the left.

Here we have described a statistical method to determine the shape of a

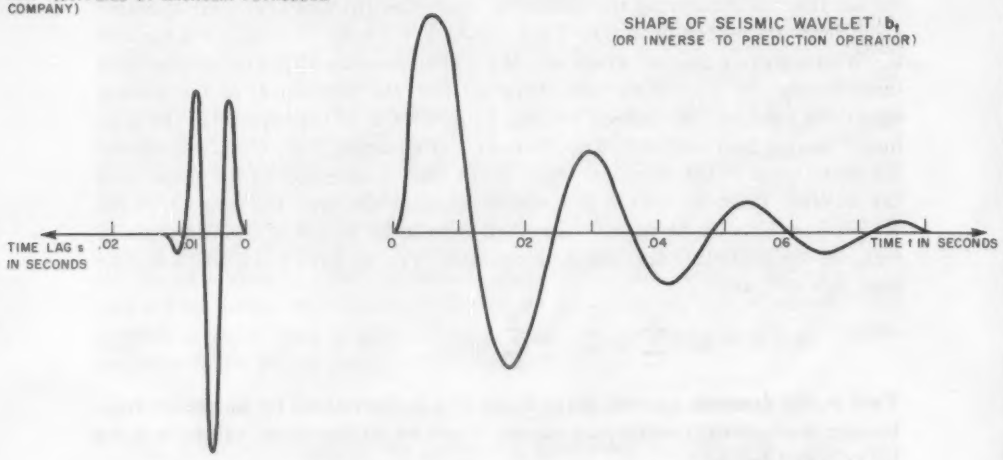

FIG. 1. Computation of wavelet from section of trace on M.I.T. record No. 1. (Supplied by the Magnolia Petroleum Company.)

Ricker wavelet. Alternatively, from other considerations, one may know in advance the shape of the seismic wavelet b_t. Then, if b_t is a realizable, stable, minimum-phase linear operator, the prediction operator or inverse wavelet shape, a_t, may be computed directly by means of equation (5). We note that in practice the wavelet must be represented by a finite operator $b_0, b_1, \cdots b_m$ and this finite operator is minimum-phase if and only if its associated homogeneous difference equation is mathematically stable or semistable.

DETECTION OF REFLECTIONS

So far we have confined ourselves to a section of seismic trace called the operator time interval which we assume to be stationary. The prediction operator transforms this section of trace into the uncorrelated prediction errors $b_0\epsilon_t$, the mean square value of which is a minimum. As we have seen, the operator cannot predict from past values of the trace the initial arrival of a new wavelet, and thus a prediction error $b_0\epsilon_t$ is introduced at the arrival time of each wavelet. Neverthe-

less, for times subsequent to the arrival time of the wavelet, the prediction operator which is the inverse to the wavelet can perfectly predict this wavelet, thereby yielding zero error of prediction. Nevertheless, a seismic trace is not made up of wavelets which have exactly the same form and which differ only in amplitudes and arrival times. Thus if a prediction operator, which is the unique inverse of a certain wavelet shape, encounters a different wavelet shape, the prediction error will no longer be an impulse, but instead will be a transient time function. Thus the prediction errors yielded by this prediction operator acting on a time series additively composed of wavelets of different shapes will not have a minimum mean-square value. Since reflected wavelets in many cases have different shapes than the wavelets comprising the seismic trace in a given non-reflection interval, a prediction operator determined from this non-reflection interval (the operator time interval) will yield high errors of prediction at such reflections. Such a procedure provides a method for the detection of reflections (Wadsworth, et al, 1953). In the figures presented there, running averages of the squared prediction errors are plotted for least-square prediction operators determined from the indicated operator time intervals. The peaks on these prediction error curves indicate reflections on the seismogram. Since two-trace operators were used there, the empirical coherency existing between the two traces was utilized in the determination of these prediction errors. Since only the information existing in the operator time interval is utilized in the determination of linear operators by this method, one may expect greater resolving power if more information on the seismogram is utilized in the determination of various other types of operators.

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PHYSICAL ANALYSIS OF DEEP SEA SEDIMENTS*

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ABSTRACT

A sonic pulse system, similar to that used at Lamont Geological Observatory for seismic model experiments, was used aboard the Research Vessel VEMA during the summer of 1954 to determine high frequency seismic velocities in fresh deep sea sediment cores. Velocity profiles were obtained from 26 cores covering a wide range of lithologies and ages (Recent to Miocene). Density, porosity, median grain size, sorting, carbonate content, and salt content were also measured.

The compressional wave velocity in the ocean-bottom unconsolidated sediments studied is well represented by the equation:

$$v' = 2.093 - (.0414 \pm .0060)\phi + (.00135 \pm .00038)\gamma - (.44 \pm .15)\eta$$

where

v' = compressional wave velocity in km/sec
ϕ = median grain size in phi units
γ = percentage of HCl soluble material
η = porosity.

Many measurements gave velocities less than the velocity of sound in sea water. Most of the low carbonate samples followed a velocity-porosity relation given by the Wood (1941) equation. The regression coefficient, $-.44\eta$, agrees well with the average slope of the Wood equation over the observed porosity range. High carbonate and large median grain size samples gave velocities above that predicted by the Wood equation. These higher velocities are explained as the combined result of shear strength and low effective porosity in the samples. The highest velocities were found in slowly deposited sediments.

The degrees of sorting of the sediments had no observable effect on the seismic velocities except that unexplained variations were greater for more poorly sorted materials. No correlation between velocity and age was evident in the sediments studied.

The effect of temperature, between 40 and 80°F. on compressional velocity in sediments may be explained by changes in elastic properties of the water fraction alone. The effect of compaction in the upper 15 or 20 feet of homogeneous sediments produced a change in seismic velocity not greater than 1 or 2 percent.

Attenuation was greater in the coarse-grained high-velocity sediments than in sediments of smaller grain size.

I. INTRODUCTION

A detailed knowledge of the physical and chemical properties of deep sea sediments is of fundamental importance in the investigation of the sedimentary history of the ocean basins. Seismic refraction and reflection measurements yield some information about variations of velocity with depth in the sediment column. Semi-empirical equations relating porosity and the elastic properties of the solid particles and interstitial material to the seismic velocity in gross mixtures have been developed and tested to some extent by experiments with artificial and natural sediments. (See Patterson, 1956, and Wyllie *et al.*, 1956, for summaries of these studies.) By determining the dependence of seismic velocity on the physical and chemical properties of ocean bottom sediments that are made available

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through coring, and using this information in conjunction with the appropriate empirical equations, the velocity information gained from the refraction and reflection data can be used to infer conditions throughout the sedimentary section.

In order to obtain a basis for correlation of seismic velocities determined by refraction and reflection techniques with sediment type, a program for the determination of high frequency seismic velocities through fresh, deep sea sediment cores was initiated during the trans-Atlantic cruise of the R/V VEMA from July to September, 1954. The immediate objectives of this program were: to correlate sediment types with seismic velocities; to determine physical and chemical properties which might control seismic velocities in unconsolidated sediments; and to investigate effects of time, depth of burial, and induration on seismic velocities in sediments of a given type.

The results reported in this paper were obtained from 26 ocean bottom sediment cores which covered a wide range of sediment types. Data obtained during the cruise included:

231 compressional wave velocity measurements at laboratory temperature and pressure;
5 low temperature (46° to 55°F.) compressional wave velocity measurements;
47 density determinations:

and a qualitative description of all cores studied. Forty-five of the density samples were preserved for later analysis at Lamont Geological Observatory.

At Lamont, porosity and grain density were determined for the preserved density samples, and mechanical analyses were run on them to determine grain size distribution. Carbonate content and salt content were also determined from small samples taken as near as possible to the original density samples.

Statistics of multiple linear regression were applied to the data with seismic velocity treated as the dependent variable and carbonate content, porosity and median grain size taken as independent variables. A significant relationship was found to exist between seismic velocity and the above three independent variables. No correlation was found between seismic velocity and sorting.

The experimental results have been compared with those of others and with equations developed by Wood (1941) and Nafe and Drake (1957).

The locations of the cores used in this study are shown in Figure 1 and given in Table 1 along with water depth, age, and core length.

Also at Lamont, subsequent to the cruise, compressional wave velocities in 5 cores of varying composition and porosity were re-measured, a total of 41 measurements, in order to determine the effects of storage on the velocity. No observable change in velocity was obtained except in one core, a high porosity gray clay.

II. INSTRUMENTATION AND EXPERIMENTAL PROCEDURE

A. *Velocity Measurement*

1. *Instrumentation*

The system used for the velocity measurements is similar to that used at Lamont Geological Observatory for seismic model experiments by Oliver, Press,

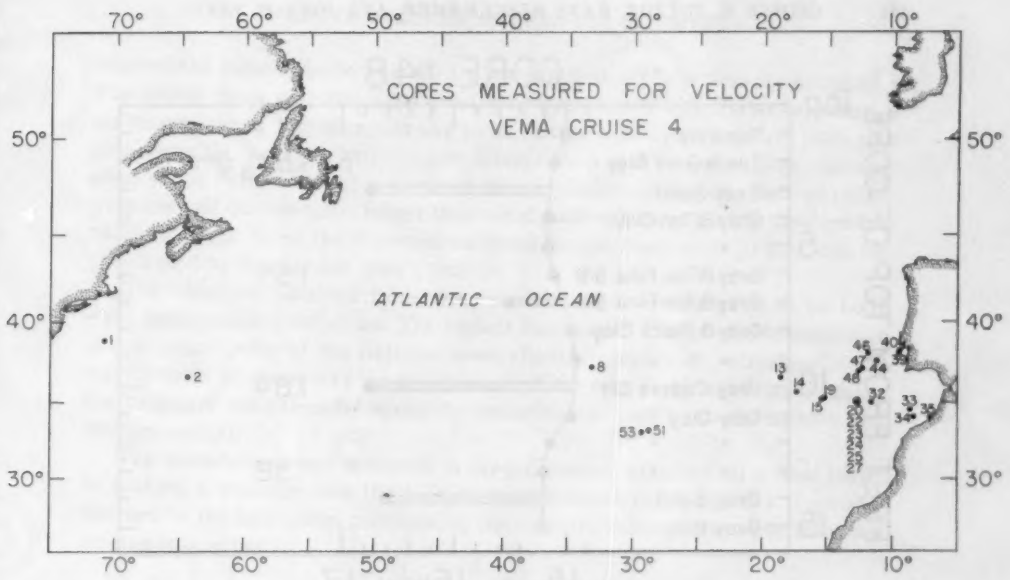

FIG. 1. Locations of cores measured for velocity on VEMA Cruise 4, summer 1954.

TABLE I

CORES MEASURED FOR VELOCITY

Core No.	Latitude	Longitude	Locality	Age*	Depth, fathoms	Length, cm
1	38°53′ N.	70°55′ W.	Continental Rise	Pleistocene	1,540	1,070
2	36°37′	64°27′	Bermuda Rise	Pleistocene	2,610	890
8	37°14′	33°08′	Atlantic Ridge	Pleistocene	910	350
13	36°36′	18°35′	N. Canary Basin	Pleistocene	2,400	410
14	35°43′	17°21′	N. Canary Basin	Pleistocene	2,300	80
15	35°11′	15°21′	Sea Mount	Neogene	1,300	245
19	35°14′	15°12′	Sea Mount	Neogene	1,600	280
20	35°08′	13°04′	Sea Mount	Neogene	940	285
22	35°08′	13°00′	Sea Mount	Pleistocene	1,200	200
23	35°01′	12°57′	Sea Mount	Pleistocene	910	380
24	35°00′	12°57′	Sea Mount	Pleistocene	580	110
25	35°01′	12°57′	Sea Mount	Pleistocene	1,200	80
27	35°03′	12°58′	Sea Mount	Miocene	700	410
32	35°03′	11°37′	Sea Mount	Pleistocene	1,220	445
33	34°35′	08°41′	Cont. Slope—Base	Neogene (reworked)	2,000	290
34	34°10′	08°16′	Continental Slope	Pleistocene	820	245
35	34°04′	08°03′	Continental Slope	Pleistocene	460	245
39	38°12′	09°24′	Lisbon Canyon	Miocene	700	165
40	38°17′	09°23′	Lisbon Canyon	Pleistocene	1,000	550
44	37°40′	11°08′	Abyssal Plain		2,550	220
46	38°05′	11°54′	Abyssal Plain	Pleistocene	2,560	85
47	37°14′	12°16′	Abyssal Plain	Pleistocene	2,570	490
48	37°02′	12°36′	Abyssal Plain	Pleistocene	2,570	490
51	33°09′	28°49′	Sea Mount	Pleistocene	500	405
53	33°06′	29°19′	Sea Mount	Miocene	1,200	365

* Age determined near bottom of core.

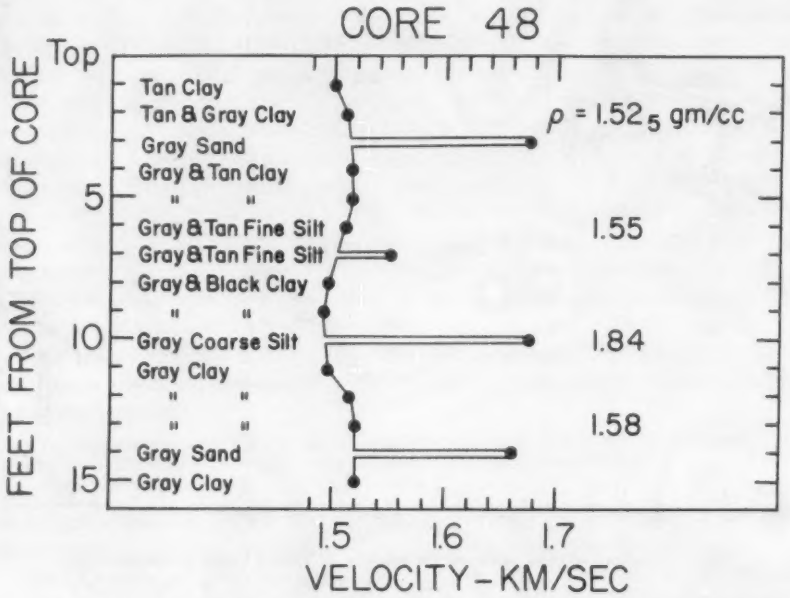

FIG. 2. Velocity vs. depth in core showing densities at appropriate depths; core 48 is from the abyssal plain near the mouth of Lisbon Canyon. High velocities and high density are from turbidity current-deposited sand layers.

Ewing (1954). A timing unit, controlled by a one-megacycle crystal, produces 1, 10, 100, etc. microsecond time marks, which are fed to the vertical plates of an oscilloscope, and trigger pulses which are fed to a pulse amplifier and to the oscilloscope sweep circuit. The pulse amplifier shapes and amplifies the trigger pulse and applies it to a transmitting transducer. The signal from a receiving transducer is amplified in a video-amplifier and fed to the vertical plates of the oscilloscope after mixing with the time marks. The repetition rate of the trigger pulses may be varied so that late arrivals from a preceding pulse will not interfere with studies of the earlier parts of the seismic wave train.

Barium titanate was used for transducers, a pulse voltage of approximately 1,200 volts being applied to the transmitting transducer.

2. *Velocity Measurements*

The velocity measurements were taken across the cores, along a diameter, with a transducer separation of 5.41 cm or 5.35 cm. Measurements were taken every foot along the core with occasional additional measurements as indicated by stratigraphic changes. A velocity standard was checked before and after measurement of each 10-foot section of core to obtain the origin time of the

transmitted pulse. (See Section II-A-4 for description of the velocity standard.) The arrival times were measured visually by comparison with the superposed 1 μ sec time markers. Amplifier gain and pulse voltage were increased until there was no observable change in arrival time. Except for a few determinations, through some of the coarse materials, in which the amplitudes of the transmitted pulses were low and the rise times longer than usual, arrival times could be measured to within 0.2 μsec. Since the transmission times ranged from 20 to 36 μsec this implies a reading error of less than 1 percent.

The velocities obtained from these measurements are believed to be body wave compressional velocities. The highest frequencies of appreciable amplitude in the initial pulse at the detector were about 1 megacycle, corresponding to wave lengths of about 0.15 cm or 3 percent of the core diameter. Also, changing the boundary conditions by manually reshaping the core produced no effect on the first arrival.

The transducers were mounted in hinged holders attached to a base plate. In making a measurement the holders were brought firmly against stops also fastened to the base plate, maintaining constant transducer separation from one reading to another.

3. *Temperature Measurements*

The effect of temperature on the compressional wave velocity in portions of

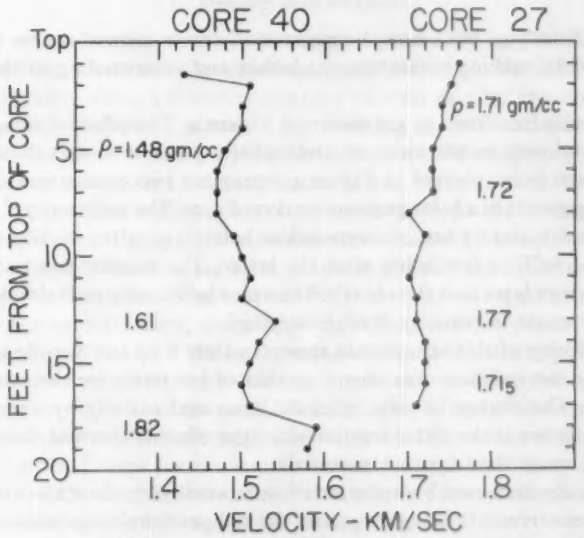

FIG. 3. Velocity vs. depth in core showing densities at appropriate depths: Core 40 is a homogeneous gray clay from the Lisbon Canyon. Core 27 is a homogeneous calcareous silt of Miocene age taken from a seamount.

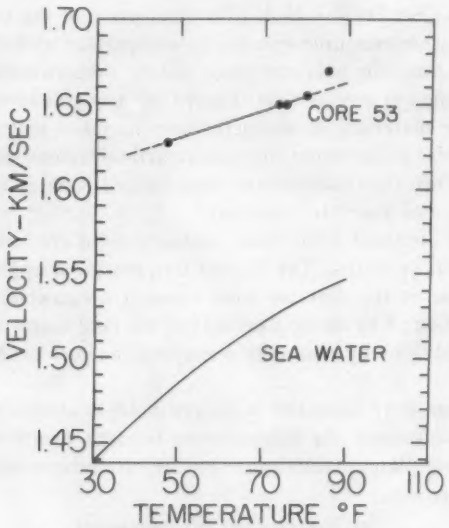

FIG. 4. Velocity vs. temperature: core 53 is calcareous and has a porosity of 0.6. The sea water curve is from Matthews (1934).

two cores, 8 and 53, both firm, homogeneous, cream-colored coarse calcisiltites, was studied by making measurements before and after cooling in the ship's refrigerator.

The results from core 53 are shown in Figure 4. The effect of temperature on the sound velocity in sea water at atmospheric pressure is also shown for comparison. Each point plotted in Figure 4 represents two measurements, taken at neighboring points in a homogeneous section of core. The points at 75° and 73.5°F. with a velocity of 1.65 km/sec were taken before and after cooling respectively and that at 80°F. a few hours after the latter. The measurement at 85°F. was taken two days later and the observed increase in velocity probably is in part an effect of decrease in porosity through drying.

The porosity of this sample was approximately 0.62 and the change in sound velocity for the sediment was about .50 that of sea water for the same temperature range. The change in velocity could be caused entirely by variation of the elastic properties of the water fraction since the effect of thermal changes is much greater for water than for rock materials.

The results from core 8 were rejected as inconclusive, the scatter in individual velocity measurements being large and the temperature range small.

Core temperatures were measured during all velocity measurements by inserting a thermometer into the sediment. Since the temperature only rarely deviated by more than 5° from 75°F., the maximum expected effect on the

velocity was less than the experimental error of the measurement. No temperature corrections were applied to the velocities.

4. *Velocity Standards and Precision*

The time zero calibration was obtained by running a travel time curve on several lengths of 1-inch diameter formica rod to determine its compressional wave velocity and using one of these pieces as a standard for determining the zero point of the triggered pulse. The travel time in the formica was a linear function of distance and gave a sharp break that could be read to 0.1 μsec. The piece used as a standard was 2.137 inches long and its measured travel time was 14.5 μsec.

The stability of the timer crystal was checked by periodically rerunning the standard travel time curve, and its accuracy was checked at Lamont by comparison with results using another timer unit which has been calibrated against WWV.

The results of the above tests indicate an accuracy of between 1 and 2 percent for the determinations of absolute velocity. However, the results from measurements of homogeneous cores indicate the precision of relative velocity determination to be considerably better and of the order of ½ to 1 percent.

B. *Physical and Chemical Analysis*

1. *Density Measurements*

Density measurements were obtained on shipboard by suspending a known volume of sediment beneath a modified spirit hydrometer in distilled water. The samples were taken along a diameter of a core where a velocity measurement had just been made. They were obtained by inserting a small transparent plastic cylinder into the core. A piston within the cylinder, held stationary at the core surface, reduced compaction to a minimum. It has been found that a negligible amount of compaction occurs when a piston is used in the coring operation (Ericson and Wollin, 1956). This should be true for both the original core and the density sample. The samples were weighed while in the cylinder with their ends exposed to the water. The volume of the samples was 5.70 or 5.78 cc, depending on the cylinder used, and their weight from 8 to 10 grams.

The weighing accuracy of the hydrometer was quite satisfactory. Precision in the density values was limited by volume determination. Since the cylinder was transparent, any voids near the surface of the sample could be seen. The ends were open and any depressions were filled with distilled water rather than air, reducing the error. Except for one sample, a poorly compacted coarse calcarenite, in which some of the sample flowed out of the cylinder, the maximum error in the density measurements is believed to be about 1 percent.

2. *Porosity and Grain Density Measurements*

Most of the density samples were sealed with wax in small glass vials after

extrusion from the plastic cylinder, and porosity and grain density were determined at Lamont.

The usual definition of porosity is the ratio of the volume of voids to the total volume. In water-saturated sediments the volume of voids is replaced by volume of water. Grain density is defined as the ratio of dry weight to the volume of the grains (i.e., total volume minus water volume).

At Lamont the total (wet) sample weights were remeasured, the samples were dried in an oven at a temperature between 100 and 114°C., and the dried samples were weighed. The wet weight determined at Lamont was consistently lower than that obtained using the density and the original sample volume, ranging from about 0.1 to 0.4 gm and averaging about 0.2 gm. This difference could be caused by loss of water from the samples, loss of sample in transfer from the density cylinder to the vials, or a combination of the two. Since the vials were sealed and no special precautions were taken in the original transfer it is quite certain that the major factor was loss during transfer.

Porosity and grain density were obtained in two ways:

Let

η = porosity
ρ_g = grain density
$\rho_w = 1$ = water density
V_0 = original density sample volume
ρ = density of wet sample
W = wet weight (measured at Lamont)
D = dry weight

Method 1—using wet weight

$$\eta = \left(\frac{W - D}{W}\right)\frac{\rho}{\rho_w} \qquad \rho_g = \frac{D\rho_w}{W\dfrac{\rho_w}{\rho} - W + D}$$

Method 2—using V_0

$$\eta = \frac{\rho V_0 - D}{V_0\rho_w} \qquad \rho_g = \frac{D\rho_w}{V_0\rho_w - \rho V_0 + D}.$$

The results from the first method averaged about 5 per cent lower than those from the second. Since the major source of error is believed to be loss in the original transfer, the results from method 1, which are not affected by this loss, have been used. Also, since any loss of solid sample in the drying procedure would tend to raise the values obtained by both methods, the use of the lower values of method 1 is preferred.

The relative error in the listed values of porosity and grain density is estimated to be about 2 percent while the absolute error could be somewhat larger.

3. *Mechanical Analysis*

A standard mechanical analysis was run on the density samples to determine the grain size distribution. The samples were divided at 74 microns. A sieve analysis was made on the coarse fraction and pipette analysis on the fine fraction. The results were plotted as cumulative frequency curves using phi units as a measure of the grain diameters, where $\phi = -\log_2$ (grain diameter in millimeters). The percentage coarser than 74 microns, median grain size, ϕ, and phi sorting coefficient, $\phi_{s0} = \frac{1}{2}\ (\phi_{75\ \text{percent}} - \phi_{25\ \text{percent}})$, were determined.* Since the pipette analyses were generally only carried to $\phi = 9$, the 75 percent cumulative frequency point was occasionally not reached and it was necessary to extrapolate to the 75 percent value for determination of the sorting coefficient.

It is difficult to estimate the error in a measurement of this kind. No repeated measurements were made. The samples were somewhat smaller than those normally used in mechanical analysis of samples in the grain size range encountered.

4. *Carbonate and Salt Content Analysis*

As mentioned in the Introduction, small (1 to 2 gm) auxiliary samples were taken from the cores as near as possible to the original density samples for determination of the carbonate content. The samples were first weighed, washed in distilled water, and reweighed so that a value for the total water-soluble salt content was also determined.

The carbonate content was then determined by treating the samples with 37 percent HCl and flushing so that in reality what was measured was the total amount of HCl-soluble material in the samples. Occasionally the filtrate was slightly colored, indicating traces of other soluble salts. However, because of the high (greater than 20 percent) percentage of soluble material which is principally calcium carbonate, the resultant percentage error must be quite small.

Since the salt content was only a small percentage of the whole (1 to 5 percent) and the measurement was merely a by-product of the carbonate content analysis, the percentage error of the values given is quite large. However, the relative values, discussed in the section on results, may have some significance.

The values given for the salt and carbonate contents are in percent by weight of dry desalted sample.

In order to compare the results of the salt content measurements it was assumed that all of the salt was dissolved in the water fraction and, using the calculated porosity and grain density, the salinity of the water fraction was computed using the following equation:

$$\text{Salinity (parts per thousand)} = \frac{10\ (\%\ \text{salt})\ (1 - \eta)\rho_g}{1.03\ \eta}.$$

* $\phi_{25\ \text{percent}}$ and $\phi_{75\ \text{percent}}$ are the grain sizes of the 25 percent and 75 percent cumulative frequency points respectively.

While the above formula is not exact, it is sufficiently accurate for treating the data presented here.

III. RESULTS

A. *Correlation of Sediment Types with Seismic Velocities*

The compressional wave velocities through the cores ranged from 1.43 to 2.77 km/sec with most of the measurements falling between 1.5 and 1.8 km/sec, a mean of about 1.65 km/sec. The cores covered a wide range of sediment types, argillaceous and calcareous lutites, siltites, and arenites.[1] Correlation between velocity and sediment type is indicated in Table II which gives a summary of the observational data for the cores on which other analyses were made.[2] The cores from this cruise were taken for the purpose of studying seamounts and turbidity current areas and are, therefore, not a representative sample of the ocean floor. The mean velocity is probably slightly high because of the influence of the older exposed sediments on the seamount flanks and the coarse turbidity current deposits. However, many of the measured velocities were less than 1.52–1.53 km/sec, the velocity in sea water under the experimental conditions.

In general the calcareous sediments showed a higher compressional wave velocity than the argillaceous and the arenites a higher velocity than the lutites. The red, tan and gray clays gave velocities ranging from 1.43 to 1.70 km/sec with a mean of about 1.55 km/sec; the argillaceous silts and arenites ranged between 1.6 and 1.7 km/sec; the calcarenites ranged from about 1.65 to 2.77 km/sec with a mean of about 1.7 km/sec. All the velocities above 1.8 km/sec were from fairly coarse calcarenites. Most of the calcareous sediments were poorly sorted globigerina ooze. The coarser calcarenites were sometimes composed of shell fragments of other marine animals. The argillites were of deep sea, continental shelf or turbidity current origin, the coarser samples being entirely limited to rather thin turbidity current layers.

The coarse samples, which in general showed the higher velocities, were sometimes quite difficult to measure, because the attenuation was high and the rise time of the initial signal was prolonged. This was noted in both calcareous and argillaceous samples. The cause was occasionally traced to cracking of the core under pressure of the transducers but apparently the attenuation is generally higher in the coarse sediments.

B. *Correlation of Sediment Types with Other Physical and Chemical Properties*

1. *Density*

Observed densities, given in Table II, range from 1.46 to 1.91 gm/cc. As may be seen in Figures 2 and 3, they usually increased slightly with depth in the cores

[1] Texture as given by the Wentworth and Krumbein scales (Krumbein and Pettijohn, 1938) is as follows:

lutite, median grain diameter less than 0.004 mm. ϕ greater than 8;
siltite, median grain diameter 0.004 to 0.063 mm. ϕ 4 to 8;
arenite, median grain diameter greater than 0.063 mm. ϕ less than 4.

[2] Table II includes about 20 percent of the velocity measurements.

TABLE II

OBSERVATIONAL DATA

Core number	Sample depth, ft.	Sample velocity, km/sec	Median grain size, Φ	Porosity, η	Carbonate content,* γ	Sorting coeff., φ SO	Density, ρ—gm/cc	Grain density, ρ_g—gm/cc	Salt content,* %	% Coarser than 74 microns	Core description
13	3	1.52	—	—	—	—	1.49	—	—	—	Red clay
13	12.5	1.59	—	—	—	—	1.71	—	—	—	White (Foram.) lutite
14	2	1.59	6.8	.65	83.4	2.4	1.60	2.72	4.8	21	Cream calcisiltite
15	3	1.68	7.4	.52	93.6	2.1	1.74	2.63	3.0	21	Cream arenaceous calcilutite
15	7	1.73	6.7	.50	91.1	1.8	1.77	2.55	2.4	20	Cream arenaceous calcilutite
15†	14	1.69	8.1	.46	93.7	1.5	1.77±	2.43	3.9	17	Cream arenaceous calcilutite
19	3	1.68	8.3?	.55	93.9	—	1.77	2.69	1.8	17	Cream calcilutite
19	7	1.68	6.3	.57	94.8	1.6	1.71	2.64	2.0	23	Cream calcisiltite
20	6	1.70	4.1	.61	94.8	2.5	1.62±	2.62	1.7	47	Cream calcarenite
22	6	1.60	7.9	.62	93.4	>3	1.57	2.50	1.4	28	Cream arenaceous calcilutite
23	3	1.80	4.2	.57	92.9	3.2	1.77	2.80	2.1	49	Cream calcarenite
23	6	1.83	3.2	.55	94.0	3.1	1.73	2.64	2.9	57	Cream calcarenite
23	12	1.77	3.3	.58	93.2	2.6	1.74	2.76	1.7	56	Cream lutaceous calcarenite
24	2	2.04	1.9	.59?	96.4	0.6	1.5±	2.2?	4.6	89	Dark buff calcarenite
24	3.5	2.77	5.1?	.47	96.4	2.2?	1.89	2.68	3.4	41	Dark arenaceous calcilutite
25	1.5	2.37	6.7?	.52	92.2	1.8?	1.80	2.67	1.8	15?	Dark arenaceous calcilutite
27	3	1.74	6.5	.57	94.9	>2.0	1.71	2.67	2.5	35	Cream calcisiltite
27	7	1.73	6.7	.57	95.4	2.4	1.72	2.69	3.7	27	Cream calcisiltite
27	13	1.71	5.3	.54	96.9	0.8	1.77	2.69	2.3	21	Cream calcisiltite
27†	16	1.72	6.1	.57	93.7	1.9	1.71±	2.65	2.0	29	Cream calcisiltite
32	3	1.75	3.8	.63	88.0	2.4	1.57±	2.57	1.4	51	Tan calcarenite
32	7	2.02	3.3	.60	88.2	2.0	1.61	2.53	4.4	60	Tan calcarenite
33	3	1.51	8.9	.68	49.2	>1.3	1.56	2.73	2.5	2	Red clay
33	7	1.62	7.5	.48	32.0	2.0	1.86±	2.67	1.3	5	Gray clay
33†	13	1.61	7.6	.47	33.2	1.7	1.90	2.69	1.0	3	Gray clay
34	1	1.61	7.3	.55	68.4	>3.6?	1.77	2.72	1.1	18	Red arenaceous clay
34	3	1.69	8.3	.54	60.6	2.4?	1.78±	2.70	2.2	17	Tan calcilutite
34†	9	1.64	8.1	.55	—	2.6?	1.77	2.73	—	14	Gray clay
34†	13	1.63	8.1	.54	74.1	2.1?	1.79	2.73	1.0	10?	Tan (white gray) clay
39	3	1.50	9.0	.70	35.2	—	1.48±	2.64	3.8	2	Gray clay
40	5	1.48	8.6	.71	32.2	2.0?	1.48	2.66	3.8	3	Gray clay
40	13	1.54	7.8	.63	28.8	1.0?	1.61	2.66	3.2	1	Gray clay
40†	18	1.59	8.4	.51	—	1.85	1.82	2.68	—	7	Gray clay
44	4	1.49	—	.74	19.5	—	1.46±	2.76	4.6	2?	Gray clay
44	6	1.59	8.3	.65	—	1.8	1.55	2.58	—	12	Gray arenaceous argilutite
46	3	1.53±	7.0	.69	33.3	1.4	1.54	2.75	2.5	10	Gray silty clay
46	8	1.51±	—	.64	32.6	—	1.61	2.69	0.9	5±	Gray silty clay
47	3	1.57	7.2	.61	23.8	1.05	1.62±	2.61	0.7	1	Gray clay
47	7	1.49	7.1	.69	20.5	2.5	1.49±	2.61	2.2	5	Tan and gray clay
47	11	1.55	8.2	.64	28.1	1.8?	1.57±	2.62	2.1	2	Tan and gray clay
47†	17	1.71	4.4	.43	—	1.5	1.91±	2.61	—	34	Gray lutaceous silt & sand
48	2	1.51	8.6	.68	25.0	1.6?	1.52±	2.62	3.4	0	Tan and gray clay
48	6	1.51	7.0	.66	22.6	1.5	1.55	2.62	4.3	0	Tan and gray clay
48	10	1.67±	4.7	.46	21.4	0.6	1.84	2.55	1.7	3	Gray coarse silt
48	13	1.52	8.3	.66	25.6	0.9	1.58	2.69	2.3	2	Gray clay
53	3	1.65	6.7	.61	97.9	2.05	1.63	2.60	0.8	28	Cream arenaceous calcisiltite
53	7	1.69	5.9	.62	96.4	1.9	1.61	2.58	1.6	33	Cream arenaceous calcisiltite

* Carbonate and salt contents are in percent by weight of dry desalted sample

† Disturbed in coring

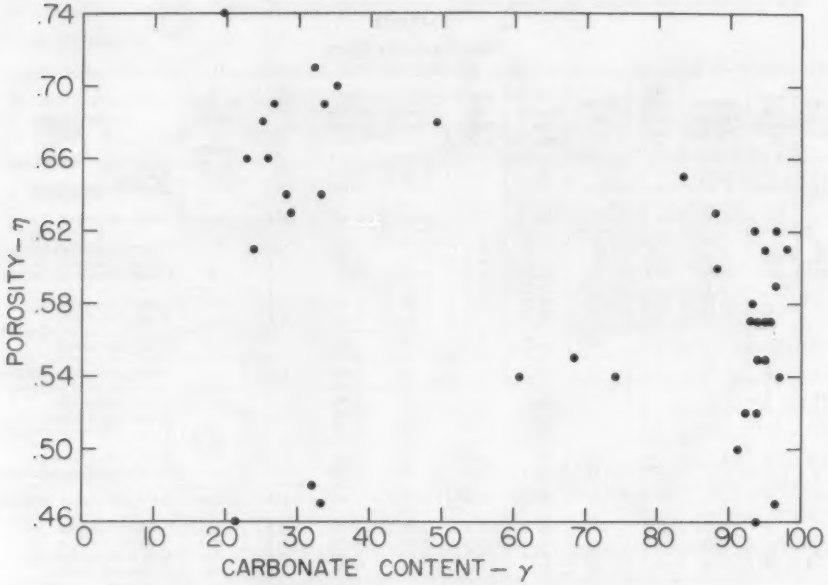

FIG. 5. Porosity vs. carbonate content.

containing homogeneous sediments and were generally slightly higher for the calcareous sediments than for the argillites. However, there were more exceptions to these relations than would be expected in uniformly deposited sediments. As mentioned above most of the cores were taken in atypical areas.

Since the grain density was relatively constant in the samples studied the variations in density were primarily the effect of changes in porosity, the two being related by the equation $\rho = \rho_g - \eta(\rho_g - \rho_w)$.

2. *Porosity*

Observed porosities ranged from .43 to .74 (Table II, Figs. 5 and 10) with a mean value of .59. As can be inferred from the previous section, the porosities tended to decrease with depth in the homogeneous cores. However, the variation between cores of a similar material was considerably larger than that found in a given homogeneous core. The calcareous materials tended to have a lower porosity, a mean of about 0.57, than the argillites, mean of about 0.62, but the scatter was very large in both types with the highest and lowest porosity values being obtained from argillaceous sediments.

There was some indication of higher porosity in the finer sediments. This trend, which has been observed in uncompacted sediments by many other workers, is obscured by the larger range of porosity values for the finer sediments.

Since many of the cores were older than Recent, some of the sediments had probably been exposed to considerable compacting pressures at some time after deposition. The expected greater compaction of the fine-grained sediments with a given compacting pressure could explain the greater porosity range.

3. *Median Grain Size*

The median grain size, ϕ, ranged from 1.9 to 9 with a mean of 6.6. The argillaceous sediments were principally silts and clays whose median grain size ranged from 4.7 to 9, the mean being about 7.6. The calcareous sediments exhibited a wide range of median grain sizes ranging from sand to clay size, 1.9 to 8.3, with a mean of about 6.2 (Table II and Fig. 6).

4. *Carbonate Content*

The carbonate content of the samples ranged from 20 to 98 percent with a mean of 67 percent. The samples fell in two groups, at 29 ± 5 percent and 94 ± 5 percent, with only a few samples falling outside these ranges (Table II and Fig. 6). Three of the samples giving intermediate values, between 60 and 75 percent, came from core 34 taken on the continental slope off northwest Africa. These

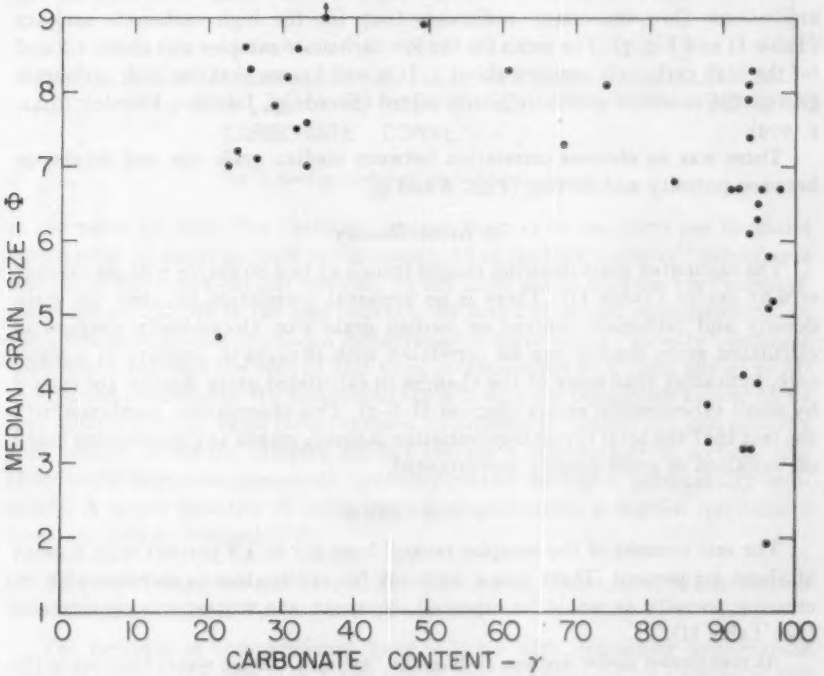

FIG. 6. Median grain size vs. carbonate content.

samples were a red arenaceous lutite, tan calcilutite, and a tan and gray clay. The only other red clay measured for carbonate, from core 33 taken from 2,000 fathoms also off Africa, had a carbonate content of 49 percent. These red clays do not seem to be the typical deep ocean "red" clays which have very low carbonate content.

The low range of carbonate content was made up from samples of gray clays, silts and sands. The high carbonate samples were mostly composed of globigerina tests.

As mentioned in section II-B-4, the values for carbonate content listed here are in percent by weight of HCl-soluble material in the dry desalted sample. These values will be slightly higher than the amount of $CaCO_3$, as determined by the standard titration method.

Samples containing more than 80 percent carbonate have been indicated by a special symbol on many of the figures.

5. *Sorting Coefficient*

The phi sorting coefficients ranged from 0.6 to greater than 3.6 with a mean of about 1.9. Although there was considerable scatter in the values obtained, there was a tendency toward better sorting (smaller sorting coefficient) for the argillaceous (low carbonate) sediments than for the high carbonate samples (Table II and Fig. 7). The mean for the low carbonate samples was about 1.6 and for the high carbonate samples about 2. It is well known that the high carbonate globigerina oozes are generally poorly sorted (Sverdrup, Johnson, Fleming, 1942, p. 979).

There was no obvious correlation between median grain size and sorting or between porosity and sorting (Figs. 8 and 9).

6. *Grain Density*

The calculated grain densities ranged from 2.43 to 2.80 gm/cc with an average of 2.65 gm/cc (Table II). There is no apparent correlation between the grain density and carbonate content or median grain size. Occasionally changes in calculated grain density can be correlated with changes in porosity in a given core, indicating that some of the changes in calculated grain density are caused by small experimental errors (Section II-B-2). This observation, combined with the fact that the total percentage variation is small, makes any conclusions based on variation of grain density unwarranted.

7. *Salt Content*

The salt content of the samples ranged from 0.7 to 4.8 percent with a mean of about 2.5 percent. There was a tendency for salt content to increase with increasing porosity as would be expected. However, the scatter was considerable (See Table II).

As mentioned under Section II-B-4, the "salinity" of the water fraction of the samples was computed assuming all of the water soluble salts had been dissolved

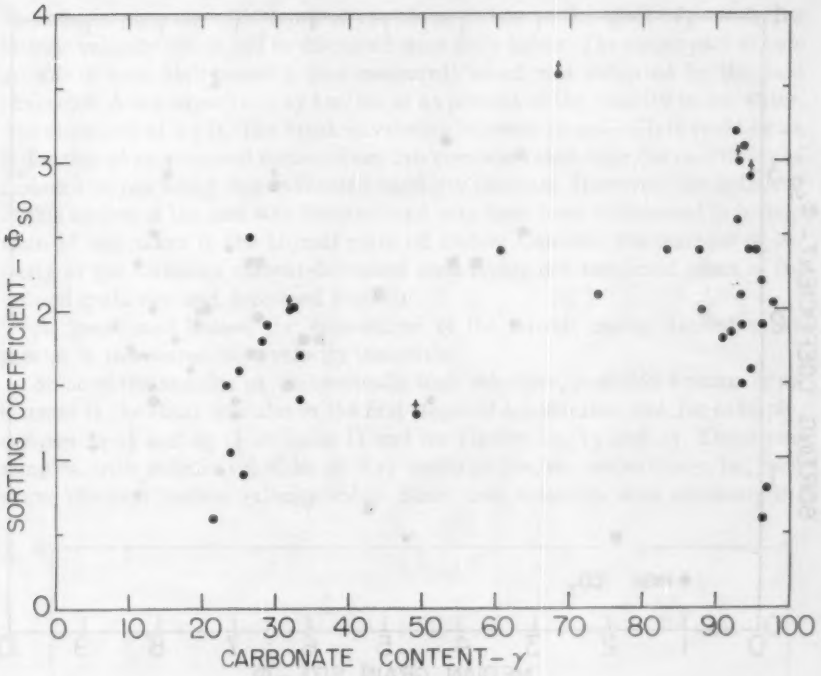

FIG. 7. Sorting coefficient vs. carbonate content.

in the water fraction. The "salinity" ranged from 11 to 105 parts per thousand with a mean of about 44 parts per thousand. All of the high "salinity" values were from high carbonate content samples. In ten cases out of thirteen the "salinity" increased with depth in the core between the first and second measurements. In the cores having more than two measurements there was a "salinity" decrease with depth between the second and third measurement in 5 cases out of 7. Although the precision of the measurements is low, these tendencies appear to be real. Evaporation of water from the cores would tend to concentrate salt near the core surface. Since the samples did not include a complete cross section, this effect might introduce some error, probably greater for higher permeability sediments. A larger quantity of more precise measurements is needed for definite conclusions to be reached.

C. *Effects of Temperature, Pressure, Depth of Burial, Induration, Water Content and Age on Seismic Velocity and Attenuation*

The decrease in compressional wave velocity with decreasing temperature found in core 53 (Section II-A-3 and Fig. 4) can be explained by changes in the elastic properties of the water fraction alone. Laughton (1954) has found that the

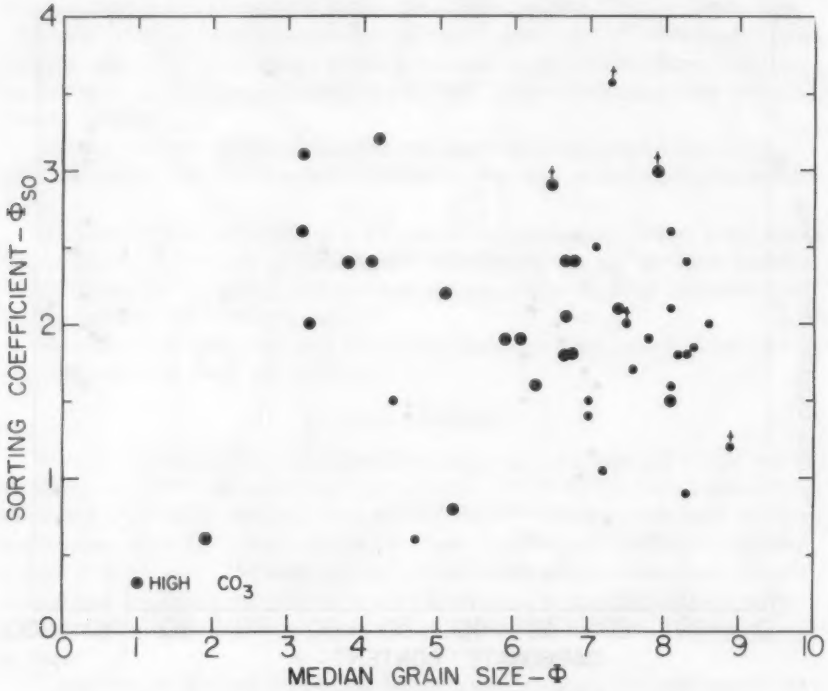

FIG. 8. Sorting coefficient vs. median grain size.

effect of hydrostatic pressure on the propagation velocity of ocean sediments can also be accounted for by changes in the water velocity alone. Since the bottom water velocities in the ocean are generally less than 1 percent different from the surface velocity, because of the combined effect of decreasing temperature and increasing pressure, the velocities given here are probably within the experimental error of those that would be found under ocean bottom conditions.

Figures 2 and 3 show velocity as a function of depth in the core for three of the longest cores measured. Density values are also listed at the appropriate depths. Except for the coarse silt or sand layers in core 48, deposited by turbidity currents, all three cores are quite homogeneous, the median grain size and carbonate content being relatively constant in the samples measured. The effect of compaction on the density is evident. The values represent a decrease in porosity with depth, excepting one unexplained decrease at 16 feet on core 27. However, there is a noticeable increase in velocity with depth only in core 40 (again excepting the sand layers in 48), with a slight decrease being observed on core 27. The effect of depth of burial on the velocity seems not to be sufficient to be generally observed in cores only 15 to 20 feet long. However, core 40, which has the greatest

decrease in porosity with depth of the three, indicates the effect of porosity on seismic velocity which will be discussed more fully below. The upper part of core 40 was of very high porosity (not measured) which was indicated by the fluid character. A low velocity, 1.43 km/sec or 93 percent of the velocity in sea water, was measured at 1.5 ft. The break in velocity between 17 and 18 feet could be an indication of an erosional surface since this core was taken near the mouth of the Lisbon Canyon which has channeled turbidity currents. However, the sediment in this section of the core was distorted and may have been compressed in coring. Core 48 was taken in the abyssal plain off Lisbon Canyon. The increase of velocity in the turbidity current-deposited sand layers is a combined effect of increased grain size and decreased porosity.

As mentioned before, the attenuation of the seismic energy tended to be greater in the coarse, high velocity materials.

Some of the samples gave abnormally high velocities, probably because of an increase in the shear modulus in the first stages of lithification. See, for example, samples 24-3½ and 25-1½ in Table II and on Figures 11, 13 and 15. These two samples, with seismic velocities of 2.77 and 2.37 km/sec respectively, fall well above the next highest velocity value. Since their velocities were obviously in-

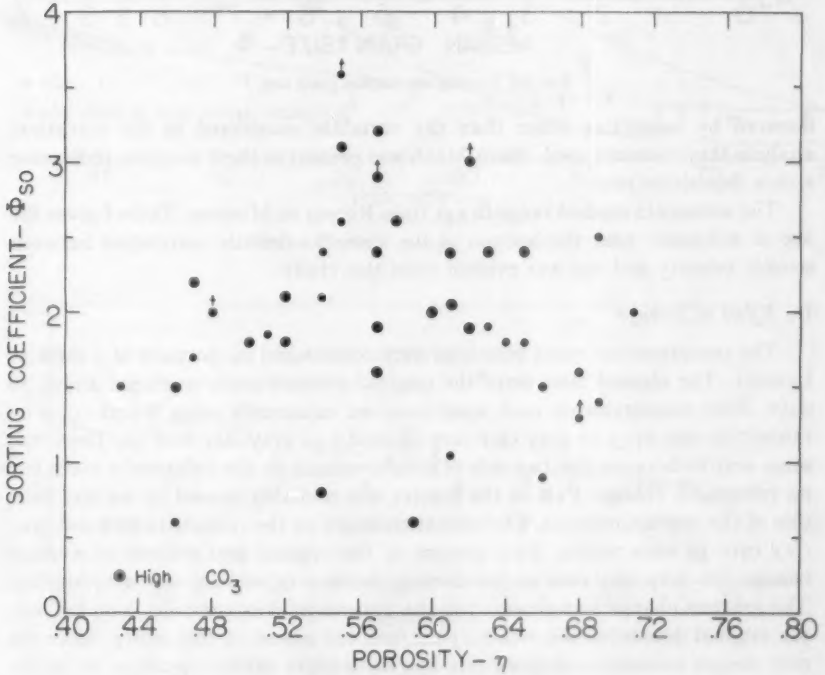

FIG. 9. Sorting coefficient vs. porosity.

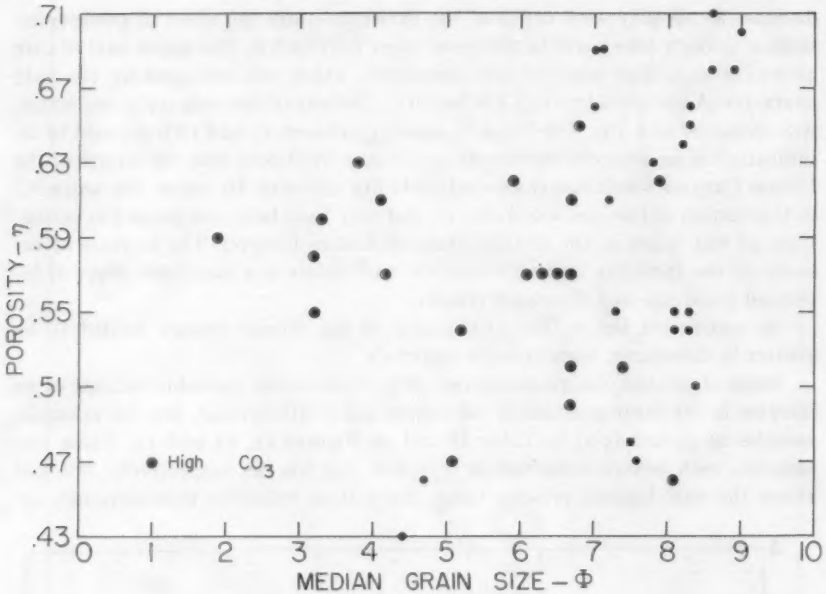

FIG. 10. Porosity vs. median grain size.

fluenced by something other than the variables considered in the statistical analysis they were not used. Black MnO_2 was present in these samples, indicating a slow deposition rate.

The sediments studied range in age from Recent to Miocene. Table I gives the age of sediments near the bottom of the core. No definite correlation between seismic velocity and age was evident from this study.

D. *Effect of Storage*

The compressional wave velocities were remeasured on portions of 5 cores at Lamont. The elapsed time since the original measurements averaged about 70 days. Nine measurements each were made on calcarenite cores 8 and 23; 9 on calcisiltite core 27; 5 on gray clay core 39; and 9 on gray clay core 40. There was some scatter between the two sets of measurements on the calcarenite cores but no systematic change. Part of the scatter was probably caused by inexact location of the remeasurements. The remeasurements on the calcisiltite core and gray clay core 39 were within ± 1.5 percent of the original and showed no average change. On gray clay core 40 the average increase in velocity was 0.03 km/sec. The greatest change was observed in the uppermost measurement, 0.09 km/sec; the original determination was 1.43 km/sec, the lowest in this study. Since the next deeper measurement gave 1.51 km/sec a slight error in position of the re-

OBSERVED VELOCITY, V–KM/SEC

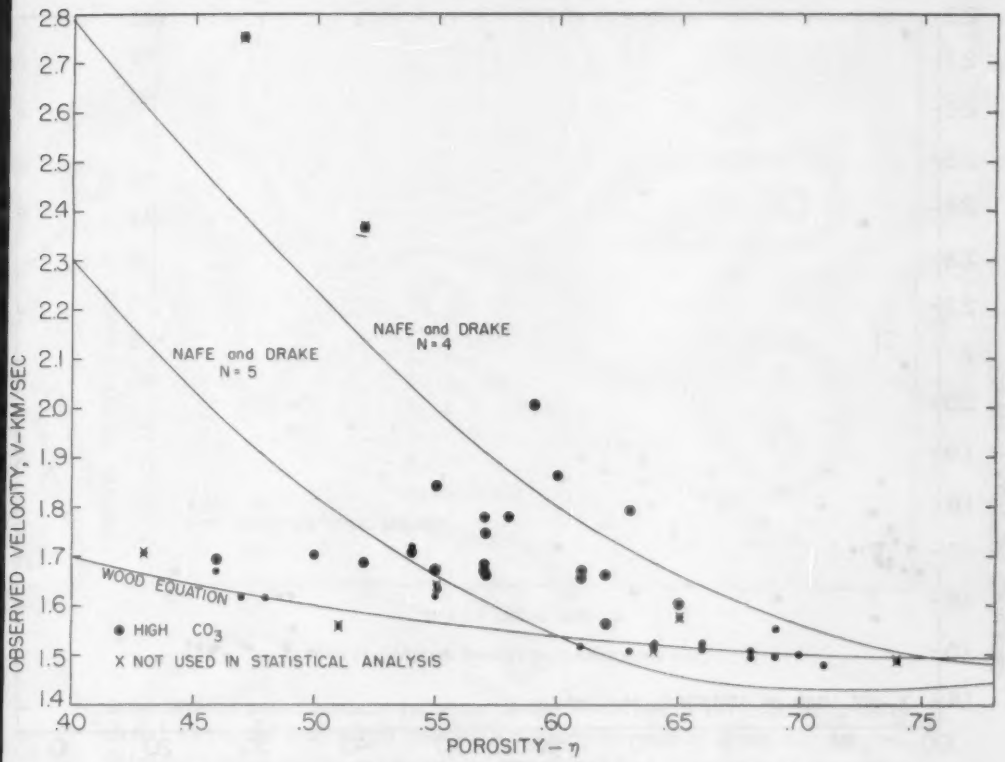
OBSERVED VELOCITY, V-KM/SEC
POROSITY – η
NAFE and DRAKE N = 4
NAFE and DRAKE N = 5
WOOD EQUATION
● HIGH CO3
X NOT USED IN STATISTICAL ANALYSIS

FIG. 11. Observed velocity vs. porosity.

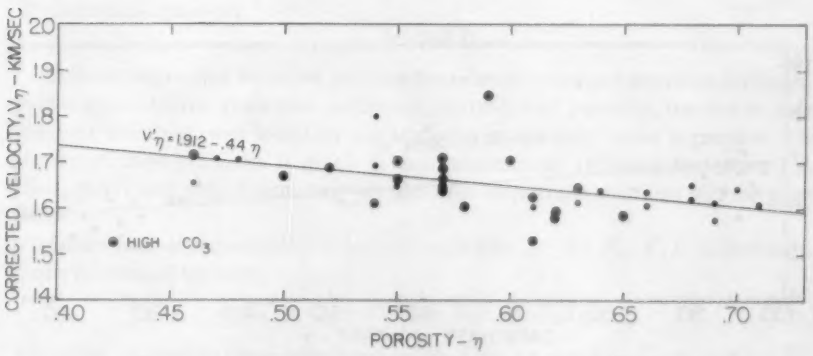

FIG. 12. Corrected velocity vs. porosity.

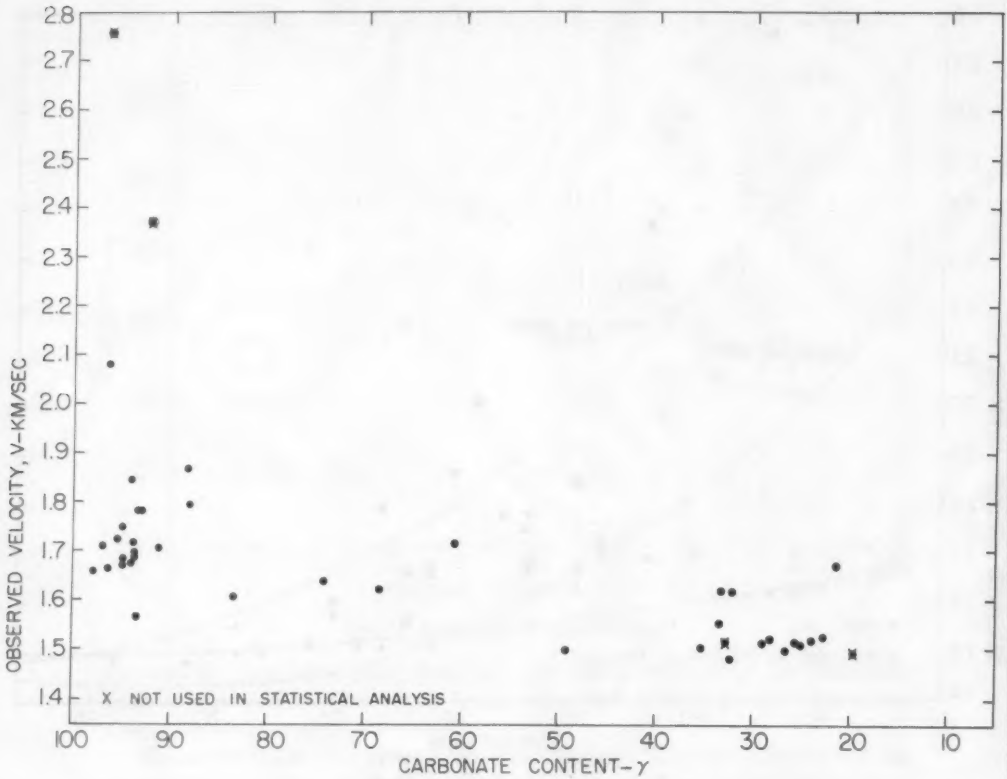

FIG. 13. Observed velocity vs. carbonate content.

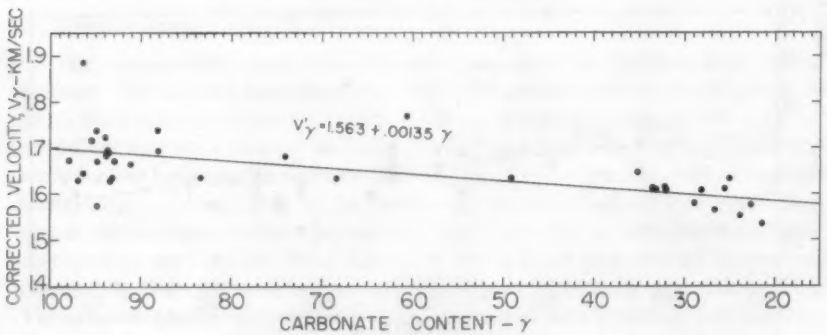

FIG. 14. Corrected velocity vs. carbonate content.

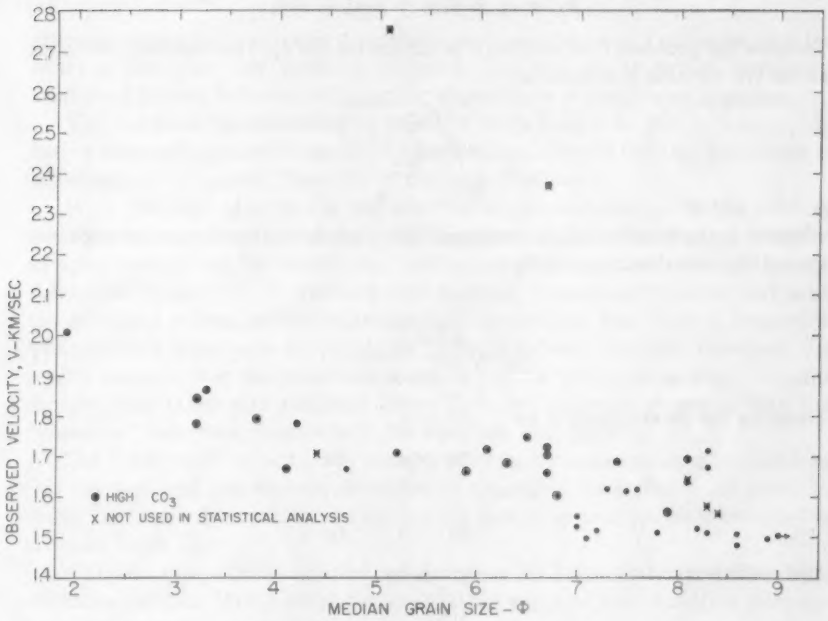

FIG. 15. Observed velocity vs. median grain size.

measurement could account for some of the deviation. A decrease in porosity during storage of 0.07 would produce a velocity increase of about 0.03 km/sec. Since the portion of core 40 remeasured was of very high porosity, 0.71, a porosity decrease is the probable cause of the velocity change.

E. *Statistical Analysis*

1. *Method Used*

A linear regression equation relating the seismic velocity, treated as dependent variable, to median grain size, carbonate content, and porosity, treated as independent variables, was found by the statistics of multiple linear regression. The theory of these statistics is given in most elementary statistics texts (see e.g., Hoel, 1951) and only a summary of the more important relations will be given here.

Given four experimentally measured variables X_1, X_2, X_3, X_4 it is desired to find a relation of the form

$$X_1' = C_0 + C_2X_2 + C_3X_3 + C_4X_4 \qquad (1)$$

where the prime denotes a calculated value. First let $x_i = X_i - \overline{X}_i$, $x_1' = X_1' - \overline{X}_1'$, where $\overline{X}$ and $\overline{X}'$ are average values. Then $X_1 - X_1' = x_1 - x_1'$ and from equation (1)

$$x_1' = a_0 + a_2x_2 + a_3x_3 + a_4x_4 \tag{2}$$

To solve the problem it is necessary to determine the a_i. The standard deviation of the ith variable is defined as

$$s_i = \sqrt{\frac{\sum_{k=1}^{n} (x_i)_k^2}{n}} \tag{3}$$

where n is the number of observations. The correlation coefficient between any two of the variables is given by

$$r_{ij} = \frac{\sum_{k=1}^{n} (x_i)_k (x_j)_k}{ns_is_j}. \tag{4}$$

Defining the determinant R as

$$R = \begin{vmatrix} r_{11} & r_{12} \cdots r_{14} \\ \cdot & \cdot \quad \cdot \\ \cdot & \cdot \quad \cdot \\ r_{41} & r_{42} \cdots r_{44} \end{vmatrix}$$

the coefficients of equation (2) are given by

$$a_i = -\frac{s_1R_{1i}}{s_iR_{11}}, \qquad a_0 = 0$$

where R_{ij} are cofactors of the elements r_{ij} in the determinant R. Substituting in (2) the regression equation becomes

$$\frac{R_{11}}{s_1} x_1' + \frac{R_{12}}{s_2} x_2 + \frac{R_{13}}{s_3} x_3 + \frac{R_{14}}{s_4} x_4 = 0.$$

The precision with which the regression equation predicts the values of the x_1 (or X_1) may be estimated with the multiple correlation $R_{1\cdot234}$ defined below. The standard error of estimate is given by

$$S_e^2 = S_{1\cdot234}^2 = \frac{R \sum_{k=1}^{n} (x_i)_k^2}{R_{11}(N-4)} \tag{6}$$

and the multiple correlation coefficient is

$$R_{1\cdot234}^2 = 1 - S_{1\cdot234}^2/s_1^2. \tag{7}$$

The partial correlation coefficient, defined as

$$r_{ij\cdot kl} = -R_{ij}/\sqrt{R_{ii}R_{jj}} \tag{8}$$

gives an estimate of the linear dependence between the i and j variables with the effect of the other two variables removed. The sign of the partial correlation coefficient merely indicates whether the dependence is positive or negative.

The values of the correlation coefficients range from 0 to ± 1, with zero indicating no correlation and 1 perfect correlation, and depend both on the scatter of the observed values and the slope of the regression line.

With the hope of reducing the effect of experimental error in the velocity measurements, an average of the velocity measurements near the points where samples were taken for density and carbonate determination was used as the "observed" velocity, v, in the statistical analysis. Homogeneity of the core near the sampling points, estimated from visual inspection, was used to determine what velocity measurements would be included in each average. However, the results indicate that the velocities measured at the points from which density samples were taken give a slightly better fit to the regression equation than the "observed" velocities, from which the equation was derived.

The "observed" velocity, the number of velocity measurements included in this average, and the average deviation of the velocities included are given in Table III. The velocity found at the density sampling point (sample velocity) is given in Table II.

With the exception of samples 24-3½ and 25-1½ which had abnormally high velocities (Section III-C), all of the samples for which all four variables were determined were used in the statistical analysis.

2. *Velocity Dependence on Grain Size, Porosity, Carbonate Content and Sorting Coefficient*

A summary of the statistical analysis is given in Table IV. The multiple regression equation

$$v' = A + B(\phi - \bar{\phi}) + C(\gamma - \bar{\gamma}) + D(\eta - \bar{\eta}) \qquad (9)$$

where

$$A = \bar{v} = 1.653 \text{ km/sec} \qquad \bar{\phi} = 6.58$$
$$B = -.0414 \pm .0051 \qquad \bar{\gamma} = 67.2$$
$$C = .00135 \pm .00030 \qquad \bar{\eta} = 0.591$$
$$D = -.44 \pm .14$$

shows that velocity increases with increasing median grain size (decreasing ϕ), increasing carbonate content, γ, and decreasing porosity, η. Observed velocity is plotted as a function of each of the independent variables in Figures 11, 13 and 15. The relations given by the regression equation are indicated on these plots but the scatter, caused principally by the influence of the other two variables, is quite large.

Corrected velocity is plotted as a function of the independent variables in

TABLE III

STATISTICAL REDUCTION OF OBSERVATIONAL DATA

Core number	Sample depth, ft.	Number of velocity measurements included in observed velocity	Average deviation of velocities included in observed velocity	Observed velocity, v—km/sec	Calculated velocity, v'—km/sec	Deviation of observed from calculated velocity, $(v-v')$—km/sec
13	3	11	.016	1.533	—	—
13	12.5	2	0	1.590	—	—
14	2	4	.019	1.603	1.643	−.040
15	3	4	.017	1.688	1.684	.004
15	7	7	.018	1.703	1.723	−.020
15†	14	5	.005	1.694	1.687	.007
19	3	5	.014	1.674	1.640	.034
19	7	4	.008	1.685	1.706	−.021
20	6	7	.174	1.670	1.785	−.115
22	6	9	.015	1.564	1.624	−.060
23	3	3	.013	1.780	1.796	−.016
23	6	5	.021	1.844	1.851	−.007
23	12	5	.012	1.780	1.833	−.053
24	2	2	.040	2.080	1.886	.194
24	3.5	2	0	2.770	—	—
25	1.5	1	—	2.370	—	—
27	3	4	.008	1.747	1.699	.048
27	7	5	.010	1.722	1.697	.025
27	13	4	.005	1.710	1.772	−.062
27†	16	3	.005	1.717	1.715	.002
32	3	4	.114	1.793	1.782	.011
32	7	4	.115	1.865	1.808	.057
33	3	5	.017	1.496	1.490	.006
33	7	4	.043	1.615	1.611	.004
33†	13	6	.014	1.618	1.616	.002
34	1	2	.010	1.620	1.643	−.023
34	3	4	.023	1.715	1.590	.125
34†	9	3	0	1.640	—	—
34†	13	6	.012	1.637	1.618	.019
39	3	5	.007	1.502	1.465	.037
40	5	9	.018	1.480	1.470	.010
40	13	7	.007	1.511	1.534	−.023
40†	18	3	.033	1.560	—	—
44	4	1	—	1.490	—	—
44	6	3	.046	1.578	—	—
46	3	3	.011	1.552	1.549	.003
46	8	5	.014	1.515	—	0

† Disturbed in coring.

TABLE III—(*continued*)

Core number	Sample depth, ft.	Number of velocity measurements included in observed velocity	Average deviation of velocities included in observed velocity	Observed velocity, v—km/sec	Calculated velocity, v'—km/sec	Deviation of observed from calculated velocity, $(v-v')$—km/sec
47	3	6	.023	1.517	1.557	−.040
47	7	3	.011	1.498	1.531	−.033
47	11	5	.011	1.522	1.514	.008
47	17	4	.014	1.708	—	—
48	2	3	.006	1.508	1.471	.037
48	6	3	.017	1.525	1.541	−.016
48	10	3	.007	1.670	1.726	−.056
48	13	4	.009	1.513	1.499	.014
53	3	4	.006	1.659	1.680	−.021
53	7	8	.009	1.663	1.710	−.047

Figures 12, 14 and 16. The corrected velocity for a given independent variable was obtained by subtracting from the observed velocity the effect of the deviation of the other two independent variables from their mean values. For example, the corrected velocity as a function of porosity is given by

$$v_\eta = v - B(\phi - \bar{\phi}) - C(\gamma - \bar{\gamma}). \tag{10}$$

The equations for the simple regression lines shown in the figures are obtained by substituting the mean values for the other two independent variables in the multiple regression equation, e.g.

$$v_\eta' = A - D\bar{\eta} + D\eta. \tag{11}$$

The reduction of scatter, resulting from removal of the effects of variation in the two variables not considered, is evident on the figures.

The velocity, v', calculated from the regression equation and the deviation of the observed velocity from the calculated velocity, $v-v'$, are listed in Table III.

The unexplained deviation was plotted versus sorting coefficient (Fig. 17) to determine whether any of the remaining scatter might be caused by this variable. No correlation is evident. However, the plot indicates that the prediction value of the regression equation may not be as good for poorly sorted sediments as for well sorted sediments. An interpretation of the velocity dependence shown by the regression equation will be given in Section F.

3. *Statistical Significance of Results*

The high value of the multiple correlation coefficient, .90 (Table 4), and the observed reduction of scatter on the graphs (Figs. 11–17) indicate that the seismic velocity is well represented by the regression equation. Observed velocity, v, would equal v' if there were perfect correlation between the observations and

TABLE IV

SUMMARY OF STATISTICAL ANALYSIS*

Raw data

Number of observations
$N = 37$

Average values

$\bar{v} = 1.653$ km/sec	$\bar{\phi} = 6.58$	$\bar{\gamma} = 67.2$	$\bar{\eta} = 0.591$

Standard deviations

$s_v = .126$	$s_\phi = 1.83$	$s_\gamma = 30.4$	$s_\eta = .0683$

Correlation coefficients

$r_{v\phi} = -.811$	$r_{v\gamma} = -.705$	$r_{v\eta} = -.469$	
	$r_{\phi\gamma} = -.494$	$r_{\phi\eta} = .199$	
		$r_{\gamma\eta} = -.343$	

Results

Regression equations

$$v' = 1.653 - (.0414 \pm .0060)(\phi - \bar{\phi}) + (.00135 \pm .00038)(\gamma - \bar{\gamma}) - (.44 \pm .15)(\eta - \bar{\eta})$$

$v_\phi' = 1.926 - .0414\phi$	when	$\eta = .591$,	$\gamma = 67.2$
$v_\gamma' = 1.563 + .00135\gamma$	when	$\eta = .591$,	$\phi = 6.58$,
$v_\eta' = 1.912 - .44\eta$	when	$\phi = 6.58$,	$\gamma = 67.2$

Multiple correlation coefficients

$R_{v\cdot\phi\gamma\eta} = .90$	$R_{v\cdot\phi\gamma} = .88$	$R_{v\cdot\phi\eta} = .87$	$R_{v\cdot\gamma\eta} = .74$

Standard error of estimate
$S_e^2 = .0030$

Partial correlation coefficients

$r_{v\phi\cdot\gamma\eta} = -.79$	$r_{v\gamma\cdot\phi\eta} = .55$	$r_{v\eta\cdot\phi\gamma} = -.54$
	$r_{\phi\gamma\cdot v\eta} = .19$	$r_{\phi\eta\cdot v\gamma} = -.35$
		$r_{\gamma\eta\cdot v\phi} = .05$

Standard deviation of observed from calculated velocities
$S_r = .052$
omitting samples 20-6, 24-2, 34-3
$S_r' = .030$

* Observed velocity $= v$
Porosity $= \eta$
Median grain size $= \phi[\phi = -\log_2(\text{grain diameter in mm})]$
Percent of carbonate by weight of dried sample $= \gamma$

the regression equation. The standard deviation of the observed from the calculated velocities, $s_r = .052$, is smaller by a factor of 2.4 than the standard deviation of the observed velocities, $s_v = .126$. By omitting samples 20-6, 24-2 and 34-3, which because of partial lithification or experimental error do not conform to the regression equation, the standard deviation becomes $s_r' = .030$, smaller by a factor of 4 than s_v. (Their omission would not appreciably affect s_v.)

A Student—t significance test[2] was applied to the partial correlation coefficients. This test indicates that correlations of velocity with grain size, carbonate content and porosity, individually, are significant at the 99.9 percent level.

[2] $$t = \frac{r_{ij\cdot kL}\sqrt{N-4}}{\sqrt{1 - r_{ij\cdot kL}^2}}$$

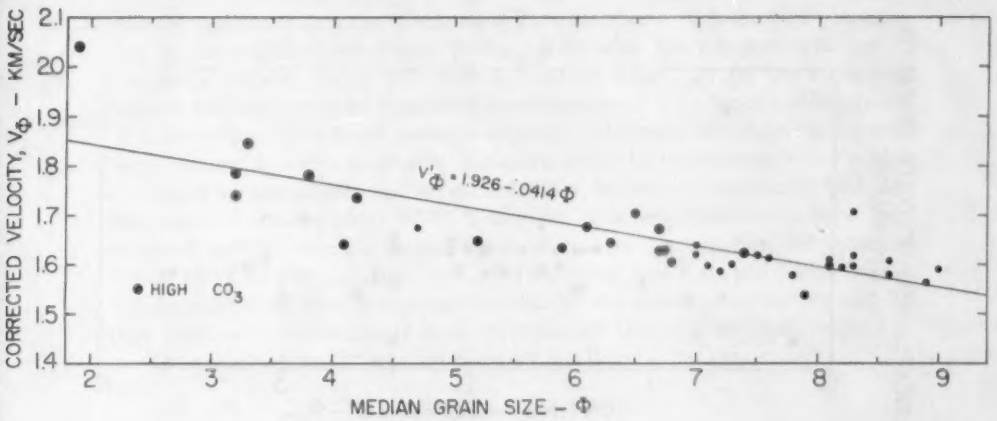

FIG. 16. Corrected velocity vs. median grain size.

Using the formulae

$$F_{1,N-2} = \frac{r_{12}^2(N-2)}{1-r_{12}^2}$$

$$F_{1,N-3} = \frac{(R_{1\cdot23}^2 - r_{12}^2)(N-3)}{1-R_{1\cdot23}^2} \tag{12}$$

$$F_{1,N-4} = \frac{(R_{1\cdot234}^2 - R_{1\cdot23}^2)(N-4)}{1-R_{1\cdot234}^2}$$

where subscripts 1, 2, 3, 4 refer to V, ϕ, γ, and η respectively; $N=37$; $R_{1\cdot23}$ is the multiple correlation coefficient considering only 3 variables; and F is the ratio of the explained to the unexplained variance; the significance of the addition of successive independent variables to explain the variance of the velocity was tested. (Since the t test and the partial correlation coefficients indicated that variation of ϕ, γ and η produced variation of v in decreasing levels of significance, this order was chosen for the F analysis of the multiple correlation.) The test demonstrated that the addition of porosity, the least significant variable, to grain size and carbonate content in explaining the variation of velocity was significant at the 99 percent level of significance.

The limits indicated for the coefficients of the multiple regression equation were determined using the formula

$$b_i - \beta_i = t\sqrt{\frac{(R_{11})_{ii}\sum_{k=1}^{n}(v-v')_k^2}{R_{11}(N-4)\sum_{k=1}^{n}(X_i-\overline{X}_i)_k^2}} \tag{13}$$

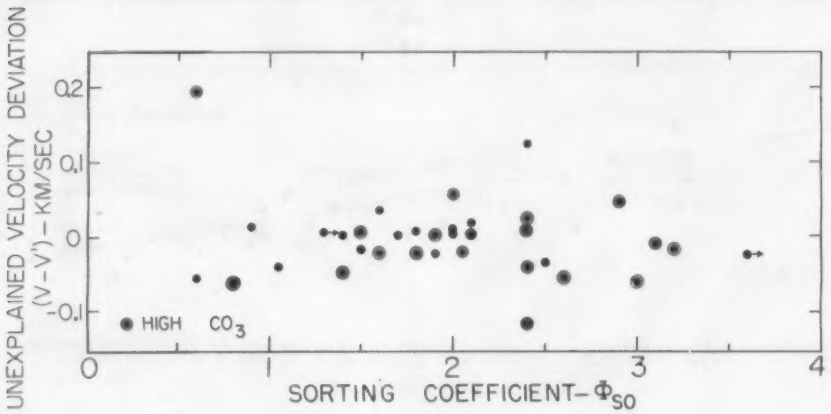

FIG. 17. Deviation of observed from calculated velocity vs. sorting coefficient.

where

$b_i-\beta_i$ is the limit in question,
$v-v'$ = deviation of observed from calculated velocity
$X_i-\overline{X}_i$ = deviation of independent variable from the mean
$(R_{11})_{ii}$ = cofactor of ii term in determinant R_{11}
t = student $-t$ factor.

A value of $t=1.053$ was used, implying a significance level of 70 percent for the number of observations, $N=37$. This level is equivalent to about one standard deviation (68 percent) for a large sample.

All tests applied indicate a strong linear dependence of the velocity on median grain size, carbonate content and porosity over the range of these variables covered by these observations.

F. *Interpretation of Results and Comparison with Other Studies*

Values of compressional wave velocities reported here agree well with those observed for ocean sediments by Laughton (1954), Hamilton (1956) and Hamilton *et al.* (1956), and by Shumway (1956). Since all of these measurements were made in the frequency range 0.03 to 1.0 mc/sec it is important to determine what differences may exist between these results and velocities found seismically with frequencies in the range 20–100 cps.

Comparison of the results of high frequency measurements of velocity both with seismic data and with theoretical velocity relations indicate that any existing dispersion is too small to be determined by the data available.

The range of velocity observed in the high frequency measurements for definitely non-lithified oceanic sediments is about 1.45 to 1.80 km/sec. There is

general agreement that the lowest values are associated with the highest porosities (in the neighborhood of 0.8). Velocity is expected to increase with increasing frequency (Officer, 1955). Velocities determined seismically for the uppermost layer of sediment must be considered as averages both over depth and horizontal distance. Normally velocity would be expected to increase with depth in the sediment column. It seems reasonable, therefore, to use for comparison with the high frequency measurements the lowest velocities determined seismically in ocean sediments. Velocities obtained by a number of seismic techniques have been reported and the minima range from 1.46 to 1.76 km/sec. See, for example, Officer and Ewing (1954), Hill (1952), Officer (1955), and Katz and Ewing (1956). The agreement between minimum velocities for the seismic observations and the high frequency measurements is an argument for lack of dispersion.

The velocity-porosity relation given by the Wood (1941) equation:[4]

$$v_{\text{Wood}} = (m\rho)^{-1/2} \tag{14}$$

where

$m = \eta m_w + (1-\eta) m_s$ (static compressibility)
$\rho = \eta \rho_w + (1-\eta)\rho_s$ (static density)
η = porosity
m = compressibility
ρ = density
subscripts w and s represent liquid and solid fractions respectively;

is derived from a compressibility valid for the static case. It is assumed that in the compressed mixture the same pressure is exerted on the fluid and the solid particles. It can be seen from Figure 11 that many of the high frequency velocity measurements follow the Wood equation

Theories for the elastic wave velocity in porous media, taking into account the effect of differential motion between fluid and solid fractions, have been developed by Ament (1953) and Biot (1956). Ament assumes the lattice to have no shear strength. The compressibility is determined as in the Wood equation. He derives a dynamic density, less than the static density, ρ, which depends upon the amount of relative movement between the fluid and solid fractions at a given frequency. The velocity given by the Ament equation reduces to the Wood velocity at very low frequencies or low permeabilities. The theory of Biot considers the compressibility and shear strength of a solid lattice, the compressibility of the liquid fraction and the effect of differential motion between solid and liquid

[4] In this and all subsequent equations for sound velocity the sediment is assumed to be gas free (water saturated). The presence of gas in a sediment reduces the velocity drastically. Some extremely low velocities have been observed in submerged sediments such as the 0.85–0.9 km/sec measured by Worzel (1951) through sediments laden with organic gas and solids in the Hudson River.

fractions. Biot's theory predicts three types of waves, two dilatational waves and a rotational wave. We are concerned here only with the dilatational wave of the first kind which has the highest velocity of the three types.

Both theories predict an increase in velocity with increasing frequency, the amount of increase at a given frequency being dependent upon the permeability of the material.

Permeability is defined by Darcy's law:

$$V = H\frac{dp}{dx} \tag{15}$$

where V = volume flow per unit area per unit time, dp/dx = pressure gradient, and H = coefficient of permeability. Another coefficient of permeability, $k = uH$, where u = fluid viscosity, which is independent of the fluid viscosity (k has dimensions of area), is often used in place of H.

Observed permeabilities of natural sediments have been reported by Creager, Justin and Hinds (1945); Stearns (1927); Wenzel and Fishel (1942). Permeability appears to be considerably more dependent upon the fine fraction than the median grain size and more or less independent of the porosity. According to Wenzel and Fishel, "Clay may contain more water per unit volume than sand or gravel, but the permeability of a clayey material is generally low. . . ."

Examination of data available in the above references indicates that materials similar to ours should have permeabilities ranging from $H = 10^{-11}$ to 10^{-6} cm⁴/dyne sec. Creager, Justin and Hinds, p. 649, present a table listing permeability as a function of the fine fraction (20 percent size). The 20 percent size of our samples, with one exception, was less than .02 mm ($\phi > 5$). According to the table this would imply a permeability, H, less than 4×10^{-8} cm⁴/dyne sec.

Biot defines a critical frequency $f_c = \eta/2\pi\rho_w H$. From the numerical examples shown in his paper one would expect an increase in group velocity of less than 1 percent for frequencies about $\frac{1}{4} f_c$ or less. Taking as a limiting case $\eta = .45$, $H = 4 \times 10^{-8}$, $\rho_w = 1$, we obtain $f_c = 2 \times 10^6$ cps or $f = 0.5 \times 10^6$ cps for less than 1 percent increase in velocity. Since this is of the order of the frequencies used in our experiments there is a possibility that velocities found for some of the coarsest, high permeability samples are higher than would have been found at lower (seismic) frequencies. However, this should not be true for the majority of the measurements, since our average median grain size was about .01 mm and the 20 percent size considerably smaller, implying a much lower permeability.

A first order approximation to the maximum velocity change predicted by Ament's theory is given by

$$\frac{v - v_{\text{Wood}}}{v_{\text{Wood}}} = \frac{2\pi^2(1-\eta)^3(\rho_g - \rho_w)^2\left[(1-\eta)\rho_w + \eta\rho_g\right]}{\eta\rho} f^2H^2 = 24f^2H^2 = .04 \tag{16}$$

when $\eta = .4$, $\rho_g = 2.65$, $\rho_w = 1$, $f = 10^6$, $H = 4 \times 10^{-8}$. Thus, a 4 percent increase in velocity over that for the low frequency limit might be expected in our samples

of highest permeability. However, since the velocity change goes as H^2, a comparatively small decrease in permeability would reduce the expected dispersion to a negligible amount.

The velocities reported here, measured at frequencies around 10^6 cps, show an increase in velocity proportional to the logarithm of the mean grain diameter. Since most theories for permeability predict that H is proportional to the square of the diameter it appears that the regression found here is not caused by frequency dependent dispersion. The theories discussed above would predict a negligible change in velocity with increasing grain size until a certain critical point where the permeability would become important. Beyond this point the velocity could rise rapidly with increasing grain size.

Laughton (unpublished) determined permeabilities from compaction experiments on ocean bottom sediments: $H = 5 \times 10^{-10}$ for a globigerina ooze; and 5×10^{-13} for a terrigenous clay. Using these values of H in equations for the Biot critical frequency and the Ament velocity, we would expect an entirely negligible increase in velocity with frequency below 10^7 cps.

The above discussion indicates that, except possibly for some localized layers of highly permeable material, near perfect coupling between the solid and liquid phases of ocean sediments, and, therefore, negligible dispersion, may be assumed from seismic frequencies to the frequencies used in the pulse techniques.

A rigorous treatment of seismic velocities in water-sediment mixtures, such as that of Biot (1956), involves some constants which are quite difficult to evaluate. Assuming lack of dispersion, as indicated above, eliminates permeability and viscosity terms and reduces the complexity of the equations. However, until something more is learned about the lattice created by grain-to-grain contact and anistropy between vertical and horizontal directions in natural ocean sediments, these theories will be of limited value. Semi-empirical equations such as those developed by Wood (1941) and Nafe and Drake (1957) may be used with considerable certainty to predict and interpret the observational data.

On Figure 11, observed velocity vs. porosity, curves from the Wood and the Nafe and Drake equations are drawn. The Wood equation, which can be written as:

$$\frac{1}{\rho V^2_{\text{Wood}}} = \frac{\eta}{\rho_w V_w^2} + \frac{(1-\eta)(1+q_s)}{\rho_s V_s^2} \qquad (14')$$

where

V = compressional velocity
ρ = density
η = porosity
$q = 4/3\ \mu/k$
μ = shear modulus
k = incompressibility
subscripts w and s represent liquid and solid fractions respectively;

is based upon the assumption that the sediment acts like an emulsion with no lattice rigidity. The limiting velocities from the equation are

$$V = V_w \text{ for } \eta = 1 \quad \text{and} \quad V = \sqrt{k_s/\rho_s} \text{ for } \eta = 0.$$

This equation predicts a minimum velocity at a porosity of about .80 that is about 3 percent lower than the sound velocity in water.

The equation is obviously not valid for low porosities, but, as mentioned above, it represents a real lower limit for velocities observed near the ocean bottom, Figure 11. It holds especially well for the low carbonate materials. The velocity-porosity dependence given by our regression coefficient, $-.44\ \eta$, is a very good straight line approximation to that given by the Wood equation over the porosity range observed here.

The equation given by Nafe and Drake is

$$\rho V^2 = \eta V^2_{\text{Wood}}[\rho + \rho_w(1 - \eta)] + \rho_s(1 - \eta)^N V_s^2 \qquad (17)$$

where N is a constant and the other symbols are defined above. This equation was developed to give a best fit for velocity-porosity data from low porosity sediments and sedimentary rocks obtained from deep wells (Wyllie *et al.*, 1956), and for higher porosity ocean sediments (Laughton, 1954, and the data presented here). This velocity approaches the Wood velocity for high porosities and approaches the solid fraction compressional wave velocity (taken here as 6.0 km/sec) for very low porosities. The equation, naturally, fits the data presented here quite well, using $N = 4$ or 5, and has been successfully used to predict shear velocities in ocean sediments. Nafe and Drake (1957) give a more detailed discussion.

The distribution of the observed velocities above values predicted by the Wood equation, equation 14, in Figure 11 is believed to be a combined effect of deviation from the emulsion assumed by Wood (i.e., the presence of some shear strength as assumed in equation 17), and an independent modification of the velocity-porosity relationship which is related to the median grain size and carbonate content of the samples studied.

The observations presented here show definite positive grain size-velocity and carbonate content-velocity correlations. Apparently this has not been noticed by other observers.[5] Even the largest grain sizes encountered here were small compared to a wave-length so that a dispersion dependent upon grain size is probably not the explanation. The possible effect of increasing permeability has been discussed above. Differences between the elastic constants and densities of the solid fraction in the high and low carbonate content samples are inadequate to explain this dependence. Since the carbonate contents of the samples were

[5] Hamilton *et al.* (1956) found a strong positive correlation between median grain size and velocity. However, since they also found a strong negative correlation between median grain size and porosity, they could explain the former relation as a combined effect of the latter and the velocity-porosity relationship.

grouped around 30 percent and 90+ percent with few values in between, the data could be represented as well by two equations, one for high and one for low carbonate content, as by the equation given.

The high carbonate samples contained a large number of hollow sub-spherical globigerina tests. Thus, for the same porosity and median grain size, a lattice predominantly of globigerina tests would be more tightly packed than a lattice of solid grains. This should increase the lattice shear strength and raise the compressional wave velocity. This effect could be considered as a decrease in the N of equation 17 or a reduction of effective porosity to a line of constant N or a combination of the two.

An interpretation of the effect of median grain size on velocity is more difficult. In most sedimentary materials the sphericity decreases with decreasing grain size. Using an argument similar to that for the carbonate dependence, we might say that given the same porosity, there would be less solid grain-to-grain contact in a fine sediment with oriented, platy grains than in a coarser sediment with more spherical grains, resulting in a lower velocity for the fine sediment. The greater ease of compaction indicated by the larger range of porosities found for the finer sediments (Section III-B-2 and Fig. 10) lends some support to this argument.

A microscopic examination of the samples showed no definite indications of partial lithification, but a slight change in the surface texture of the grains was noticed on some of the high velocity samples.

The highest velocities were found in samples with evidence of very slow deposition (traces of MnO_2). These samples did not have abnormally low porosities. This suggests that a greater time of contact with the bottom water and/or a slower rate of compaction permits an increase in the sediment shear strength for a given porosity.

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GEOPHYSICS, VOL. XXII, NO. 4 (OCTOBER, 1957), PP. 813–820, 6 FIGS.

SEISMIC VELOCITY STUDY OF SYNTHETIC CORES*

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ABSTRACT

The velocity of a longitudinal elastic wave through rock at room temperature and at atmospheric pressure depends upon the nature of the rock frame, the porosity of the rock, and the nature of the pore-filling fluid. In the present investigation longitudinal elastic wave velocities were measured for sixty synthetic cores. The rock frame consisted of sorted quartz sand grains and cement, the percentage of cement varying from ten to fifty percent. The core porosities varied from 8.8 percent to 22 percent. The velocities were measured for dry air-filled cores and for cores saturated with various liquids. These pore-filling liquids were distilled water, ethyl alcohol, benzene, carbon tetrachloride, and chloroform. The measured velocities ranged from 2,360 feet per second to 14,710 feet per second. The wave velocity in liquid-filled cores of 10 percent porosity was approximately twice the velocity for cores of 20 percent porosity, the same type of cement being used in both instances. For any given core, flooded with fluids of wave velocities ranging from 3,000 to 5,000 feet per second, the maximum observed variation in core velocity was around 20 percent. The experimental data fitted the empirical linear equation

$$V_t = kV_f + C$$

where

V_t = velocity of longitudinal elastic waves passing through the flooded core;
V_f = velocity of longitudinal elastic waves in passing through the saturating fluid.

The constant k depends upon the porosity of the rock and the type of cement used. The constant, C, depends upon the nature of the rock frame.

INTRODUCTION

Recent developments in exploration geophysics have emphasized the need for determining the fundamental relationships between the velocity of elastic waves and the properties of the materials through which the waves are propagated.

In general, the velocity of a longitudinal wave through rock at room temperature and at atmospheric pressure depends upon the nature of the rock frame, its porosity, and the nature of the pore-filling fluid. Wyllie and others (1956) investigated the effects of several parameters on the wave velocity in synthetic and in naturally occurring media. These writers presented empirical equations relating time-average velocity to the porosity of the rock, wave velocity in the interstitial fluid, and wave velocity in the rock frame. Hicks and Berry (1956) compared the velocities obtained from acoustic well logs with velocities obtained

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from natural cores taken from the logged depth intervals. These investigators concluded that a maximum change in the compressibility of the interstitial fluid may cause the velocity to vary by 15 to 20 percent; that a porosity change from 3 percent to 30 percent may result in velocity variations of 60 percent; and that velocity variations of 100 percent are possible for greater porosity changes. Denton (1956), using velocities obtained from velocity logs in limestone, obtained a "quasi-linear" relationship between velocity and porosity for porosities lying between one percent and 34 percent.

The object of the present investigation is to relate the longitudinal wave velocity to the composition parameters of small synthetic cores. These parameters include porosity, amount of cementing material, type of cementing material, and type of interstitial fluid.

EXPERIMENTAL METHODS

The instrumentation used in this investigation employs the pulse method similar to that used by Hughes and others (1949), and by Wyllie and others (1956). The arrival times of the pulses could be measured to one tenth of a microsecond. The frequencies involved in the pulse transmission were approximately 300 kilocycles.

Fabricated synthetic cores were used in this study so that the parameters which affect the elastic wave velocities could be controlled. It is difficult to control these parameters when using natural cores. A total of sixty synthetic cores were prepared in accordance with the method described by Mandel and others (1957). The solid frame of the cores was composed entirely of quartz grains and cementing material. Three cements were used in preparing the cores. These cements were obtained from the General Refractory Company and were marketed under the trade names Grefco, Alcoa, and Lumnite. The cores were one inch long and three-quarters of an inch in diameter. For each cement, cores were made containing 10, 20, 30, 40, and 50 percent of cement by volume. The sand used was sorted Ottawa sand with average grain diameter of about 0.42 mm. There were four cores for each of the fifteen compositions. Cores could not be prepared with less than 10 percent cement because of a tendency to crumble. Photomicrographs of thin sections prepared from three of the cores containing Grefco cement are shown in Figure 1. In Figures 1a, 1b, and 1c the amounts of cement used were 10, 20, and 30 percent, respectively. In these synthetic cores, the cementing material fills the interstitial void space almost completely, and the porosity is determined principally by the packing of the cement. Very few quartz-to-quartz contacts between the sand grains are observable. In other words, nearly all of the quartz grains are separated by a thin film of cement. All of these synthetic cores have this characteristic and its effect on wave velocity is unknown. When the quartz and cement are mixed, the quartz grains become coated with cement. As a result of the manufacturing process, a few of the grains are crushed as may be seen in the photomicrographs. Attention should be called to the fact that in a natural

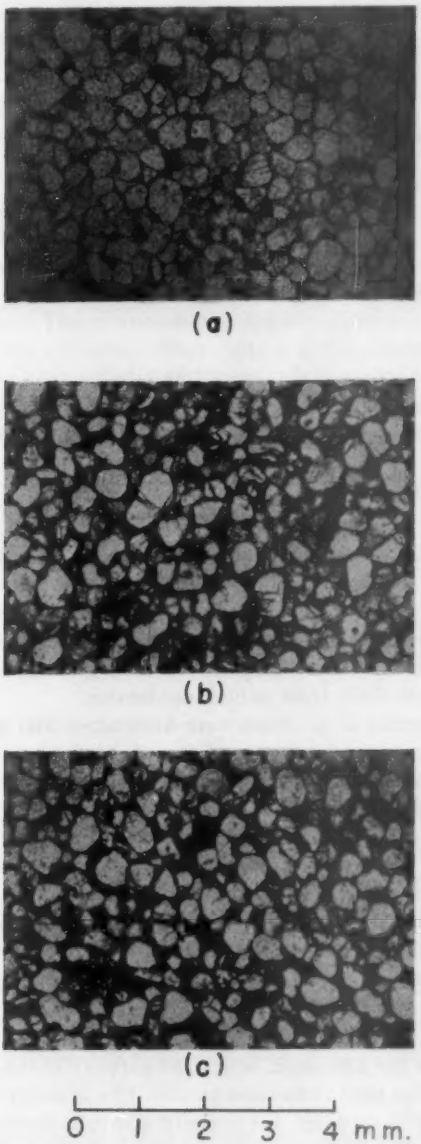

FIG. 1. Photomicrographs of thin sections of synthetic cores containing sand grains and Grefco cement. Cement content by volume is (a) 10 percent, (b) 20 percent, and (c) 30 percent.

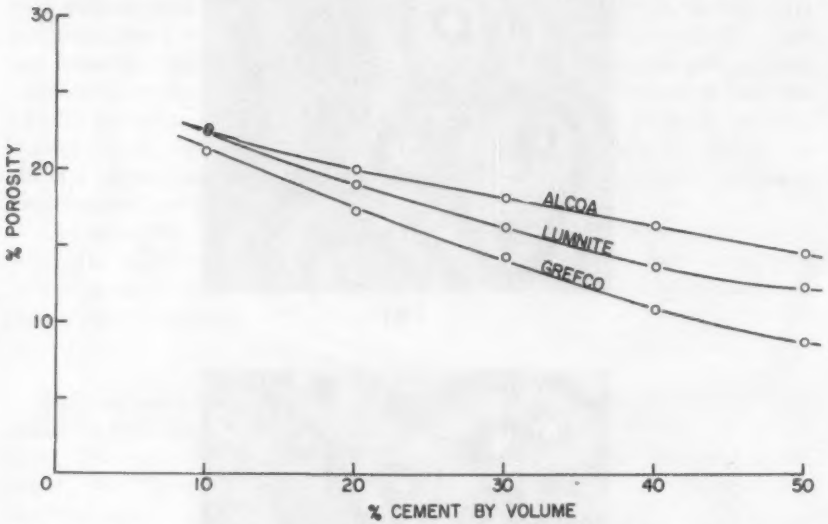

FIG. 2. Graph showing relationship between the percentage of cement by volume of synthetic cores to the porosity of the cores for different types of cement.

sandstone there are many quartz-to-quartz contacts between the sand grains so that void spaces usually exist between the sand grains. In these respects, the synthetic sandstones differ from natural sandstones.

The wave velocities in the cores were determined first with the pore spaces filled with air. These same cores were then flooded successively with distilled water, ethyl alcohol, benzene, carbon tetrachloride, and chloroform. Usually three floodings were used with each fluid. All flooding was done by introducing the fluid into an evacuated chamber which contained the cores. This, of course, prevented entrapment of air in the pore spaces. All velocity measurements were made at room temperatures between 24°C. and 26°C. and at atmospheric pressure. Two or more velocity measurements were made for each of the 60 cores with each of the pore-filling liquids. Measurements of the porosities of the cores were made by evacuation and flooding of the cores.

EXPERIMENTAL RESULTS

Figure 2 shows the manner in which the porosity of the core varies with the percentage of cement used in its construction. This is shown for each of the three cements. As would be expected, the porosity is seen to decrease as the percentage of cement is increased. The porosity is also dependent upon the type of cement. The variation in core porosity with type of cement is apparently caused by a

variation in the porosity of the cement itself. Pure cement cores, made without using any sand, show porosities as follows:

Alcoa 22 percent
Lumnite 14 percent
Grefco 2 percent

Wave velocities in water-flooded cores made of pure cement ranged from 17,000 feet per second for Alcoa cement to 18,000 feet per second for Grefco cement.

Figure 3 shows the longitudinal wave velocity as a function of the core porosity, using water flooded cores. Curves are drawn for each of the three cements used. Each plotted value for the velocity is an average of 8 or more velocity measurements. The relationship is apparently linear for each cement type except for the high porosities where there is a slight curving of the graph. This linearity between wave velocity and porosity is in accordance with the work of previous investigators (Denton, 1956; and others). The velocity in the cores of 10 percent porosity is approximately twice the velocity in the cores of 20 percent porosity.

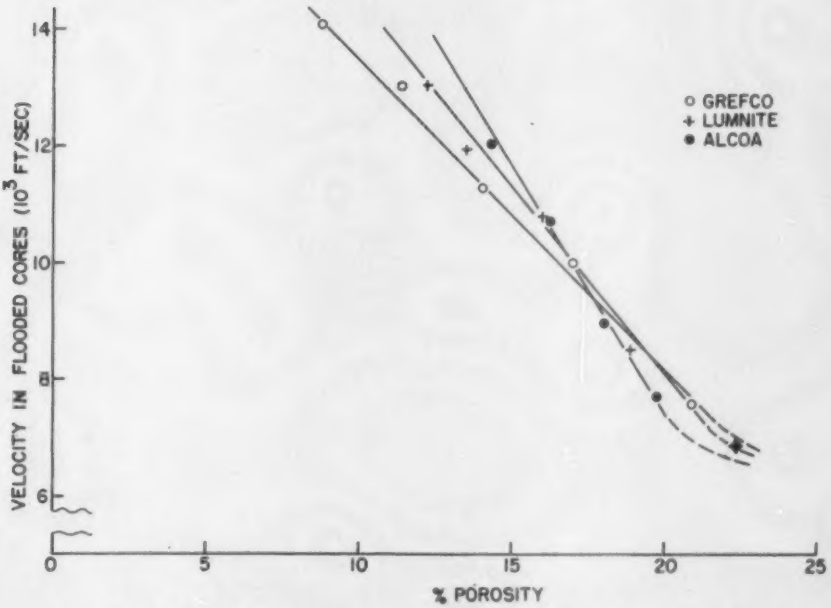

FIG. 3. Graph showing relationship between the longitudinal wave velocity through water-flooded cores and the porosity, for different types of cement.

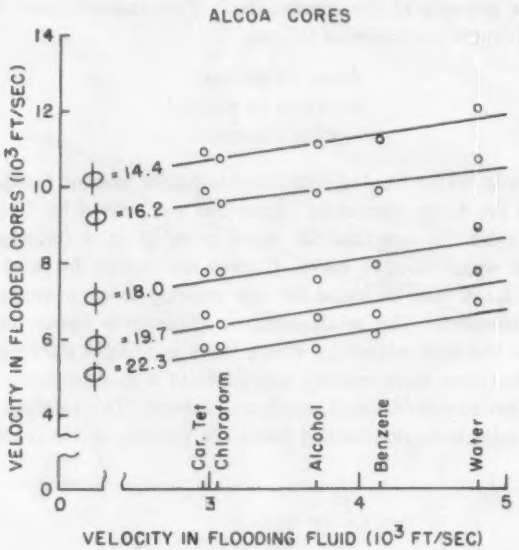

FIG. 4. Graph showing relationship between the velocities in the flooded cores and the velocities in the saturating fluid, for different porosities, ϕ (Alcoa cores).

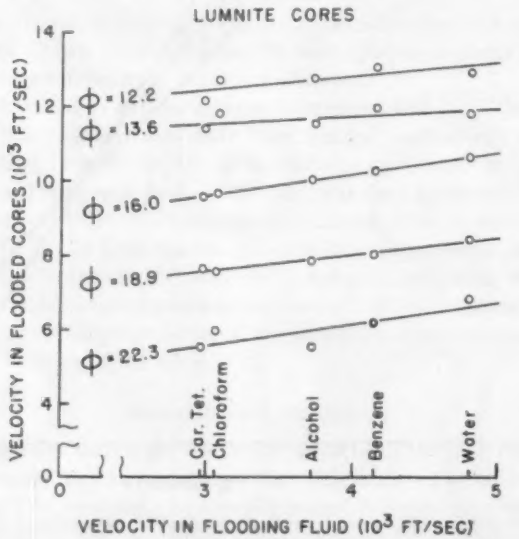

FIG. 5. Graph showing relationship between the velocities in the flooded cores and the velocities in the saturating fluid, for different porosities, ϕ (Lumnite cores).

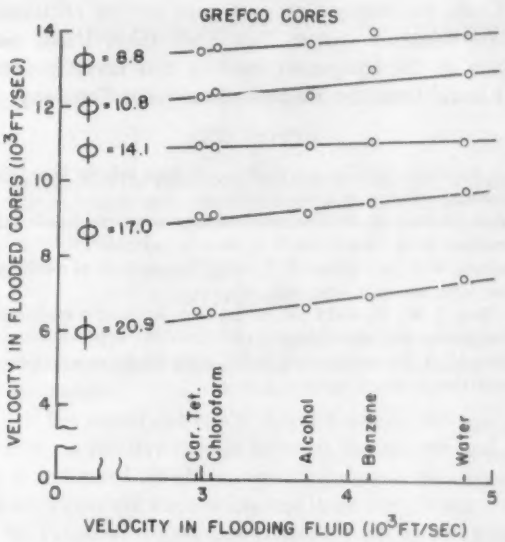

FIG. 6. Graph showing relationship between the velocities in the flooded cores and the velocities in the saturating fluid, for different porosities, ϕ (Grefco cores).

Figures 4, 5, and 6 show the wave velocities in the flooded cores, V_t, as a function of the wave velocity in the flooding fluids, V_f, for various core porosities, ϕ, and for each cement type.

The relationship between V_t and V_f appears to be linear so that

$$V_t = kV_f + C.$$

It is believed that k depends upon the porosity and type of cement and that C depends upon the nature of the frame. The quantity, k, seems to increase with increasing porosity of the core, but more data are needed to establish this relationship. For a given frame, the data indicate that k and C are reasonably constant for liquid-filled synthetic cores.

These graphs show that the maximum effect of the wave velocity in the fluids on the wave velocities in the core is around 20 percent. Much larger changes in core velocities (over 100 percent) can be seen for the range of porosities given on these graphs. These observations are in accordance with those of Hicks and Berry (1956). It is thought that this variation of velocity with porosity is intimately associated with the amount and type of cement present in the cores in that the cement affects the elastic constants of the cores.

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GEOPHYSICS, VOL. XXII, NO. 4 (OCTOBER, 1957), PP. 821–828, 6 FIGS.

THE ABSORPTION OF SOUND IN SEDIMENTS*

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ABSTRACT

Measurements were made of the attenuation of sound in compacted sediments in water using an ultrasonic wave train at frequencies in the megacycle range. Artificial sediments of glass spheres as well as marine sands have been tested and the variation of absorption with frequency, mean grain size, and concentration are illustrated.

INTRODUCTION

Lamb (1916) obtained a formula for the attenuation of a plane sound wave passing through a suspension of mobile solid spheres in a fluid. This attenuation he ascribed to two causes:

a. Scattering of the sound out of the direct beam by the spheres,

b. Loss of energy in relative motion between the spheres and the fluid.

Urick (1948) investigated the absorption of ultrasonic radiation in suspensions of solid particles such that the viscous loss was large and the scattering negligible. He found that, for values of the volume concentration up to 15 percent, the absorption was proportional to the concentration as predicted by the theory of Lamb. For higher concentrations, the viscous absorption reached a maximum value and then decreased. This effect was attributed to the interaction between the particles which had been neglected in the theory of the viscous absorption. For suspensions of particles of a size such as to make the scattering large and the viscous term small, the theoretical treatment again neglects the interaction between the particles. The theory predicts a linear relationship between absorption and concentration, which has also been confirmed for concentrations of up to 15 percent by volume.

If the interaction between the particles is taken into account, as it must be for high concentrations, the mathematical treatment of the ultrasonic absorption in suspensions becomes extremely complex. Some effects may be visualised on purely physical grounds, for example:

a. Multiple scattering will become important and may reduce the absorption, since energy diverted from the acoustic beam may impinge upon another particle and be returned to its original path.

b. The mobility of the particles will be altered since the probability of collision is increased at high concentrations.

MEASUREMENTS OF ATTENUATION

It has been possible to measure experimentally the absorption in sediments and suspensions of high concentration for a limited number of particle sizes and

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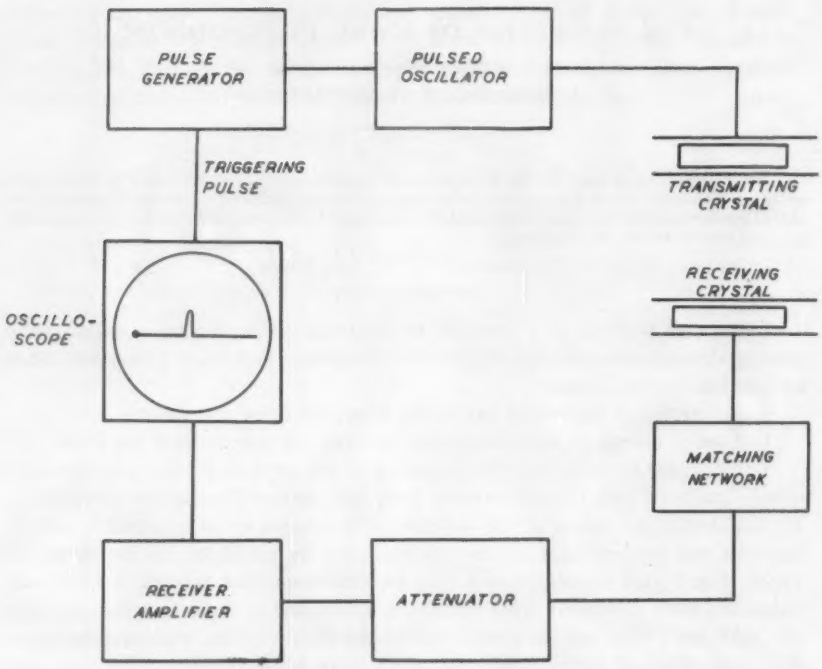

FIG. 1. Block diagram of ultrasonic wave-train circuit.

frequencies. The results show the effect of interaction between the particles in the sediment on the attenuation.

Measurements in suspensions of high concentration

In the experimental investigation of this relationship, a short wave train of ultrasonic waves was used.

Most previous investigators using an ultrasonic wave train have used a single crystal vibrating at its natural frequency as both transmitter and receiver, but in the present work a pair of matched quartz crystals was used, one to transmit and one to receive. This removed difficulties due to the transmitted train passing into the receiver circuit and causing saturation. Crystals for six discrete frequencies, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 megacycles per second were available.

A block diagram of the apparatus is shown in Figure 1. The transmitter section comprises an asymmetrical multivibrator and an electron-coupled Hartley oscillator for generating trains of radio-frequency voltage. The length of these trains could be varied between 2 and 25 milliseconds. The receiver section consisted of

i. A network to match the 75 ohm input impedance of the attenuator to the impedance of the crystal,

ii. An attenuator reading to 0.60 decibels in steps of 0.5 decibel,

iii. A frequency converter, and

iv. An intermediate-frequency amplifier.

The received train, after detection, is displayed on a double-beam oscilloscope using a time-base triggered from the pulse-generating circuit.

Readings were taken by moving the crystals apart to the maximum required distance, setting the received signal to a reference line on the oscilloscope, increasing the electrical attenuation, and then reducing the separation until the signal was brought down to its former level by a decrease of the acoustic attenuation. By this means a graph of attenuation against distance-moved may be plotted, and from the slope of this graph the absorption may be calculated.

Some divergence of the sound beam was encountered, particularly at the lower frequencies. An empirical correction was made for this divergence from a series of measurements in distilled water, for which the absorption coefficient is accurately known.

Measurements in artificial and natural sediments

Because of its interest to geophysicists, measurements were started in 1951 by one of us (Busby, 1954) on sediments contained under water in a glass cell. After this work was completed, Shumway (1956) published some data on the absorption in a sediment-filled resonator at lower frequencies, based on some theoretical work of Toulis (1956).

For sediments, our apparatus was of the form shown in Figure 2. The acoustic path was vertical and the crystals were kept a fixed distance apart. The lower crystal was pressed against a machined brass collar and the joint made watertight with silicone grease. The upper crystal was contained in a holder which was rigidly clamped in position. The glass tube was filled with water, and the crystals were aligned by means of the levelling screws shown in the diagram. The sediment was allowed to settle in a uniform layer to the bottom of the cell, and the increase in attenuation was measured using a "null" method with the calibrated electrical attenuator as a compensator. By adding successive quantities of sediment and by measuring the increase in the depth of the sediment, graphs of attenuation against path length in the sediment could be plotted. These graphs were linear. Any effect due to the acoustic mismatch at the liquid-sediment interface which is always present, has a constant value and so should not affect the slope of these graphs. This method of measurement avoids the use of short acoustic path lengths and the difficulties due to the overlapping of the reflected wave trains.

The accuracy of the readings is limited by the measurements of the sediment depth. These depth measurements were made with a graduated scale. More accurate methods, such as the use of a vernier microscope, were of no advantage because of small irregularities in the surface of the sediment.

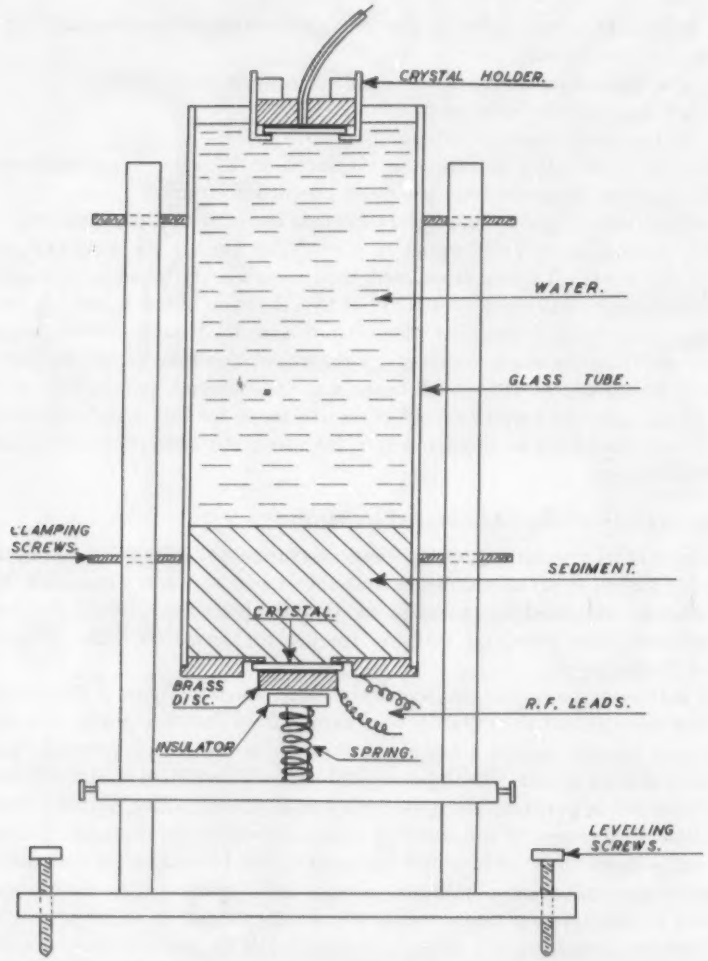

FIG. 2. Apparatus for measuring attenuation in sediments.

The absorption in natural sediments is high and it increases with frequency. The highest frequency at which the absorption could be measured was 3.0 megacycles per second. The lower limit of frequency was approximately 500 kilocycles per second, since below this value the interrupted wave train method of measurement is unsatisfactory. At these low frequencies the water absorption is negligible but the acoustic beam is divergent. It was assumed that any change in the di-

vergence due to insertion of the sediment was negligible compared with the high absorption measured. If this is so, then the use of a fixed path length eliminates errors due to the spreading of the beam. The type of graph obtained from a plot of attenuation against path length is shown in Figure 3. This is for a sediment composed of glass spheres (diameter 120 microns) in water at 2 megacycles per second. Similar graphs were obtained for these spheres at 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 megacycles per second. The slopes of the curves give the attenuation in decibels per centimeter, and these attenuations are shown plotted against the frequency in Figure 4. The gradient of this curve is small below 1.5 megacycles per second and rises sharply above this value. Experiments were attempted at

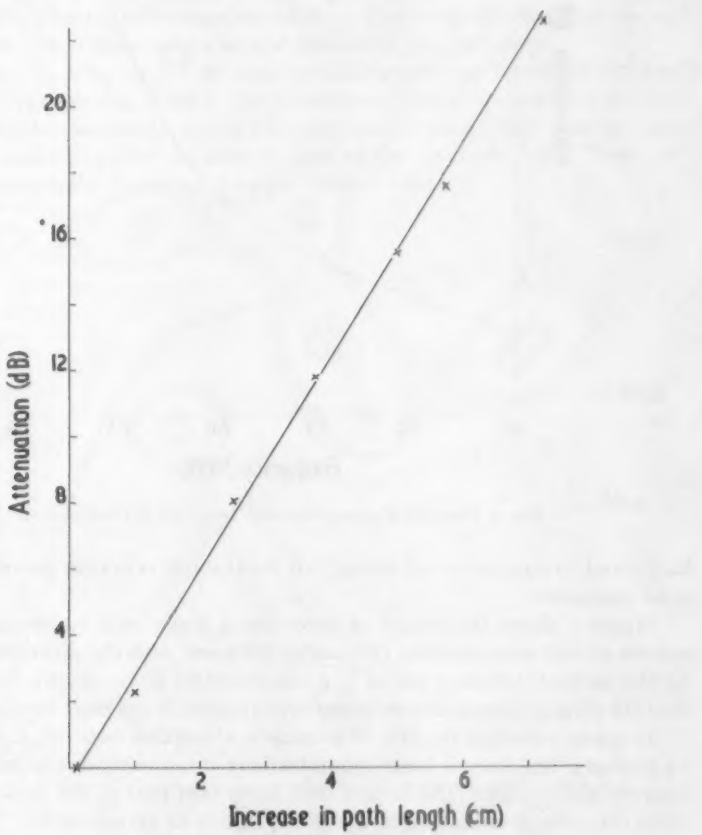

FIG. 3. Variation of attenuation with path length in sediments of glass spheres (diameter 120 μ) in water at 2 megacycles per second.

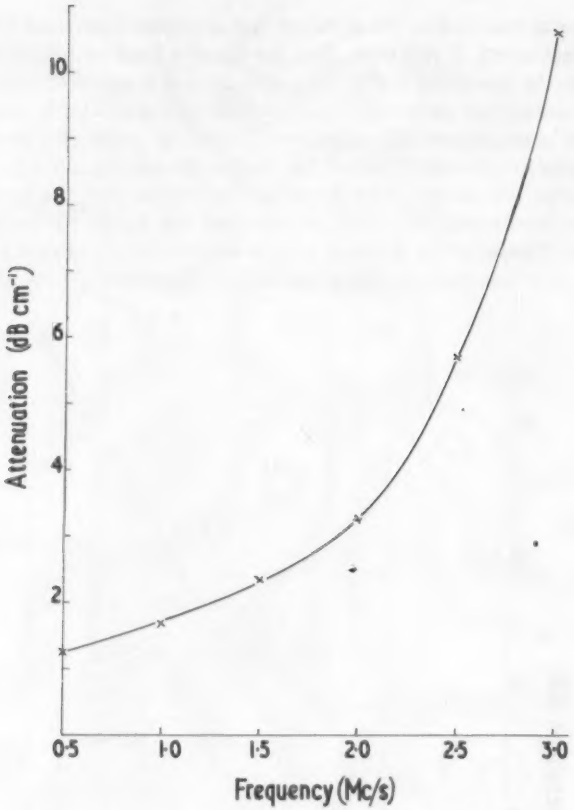

FIG. 4. Variation of attenuation with frequency in a sediment.

both 6 and 10 megacycles per second but the absorption in each case was too high to be measured.

Figure 5 shows the results of experiments made with suspensions of glass spheres at high concentration (plotted as full lines) with the experimental values for the artificial sediment added at a concentration of 74 percent. It is assumed that the glass spheres in the sediment are arranged in the most compact manner.

It can be seen that the rate of increase in absorption between 40 percent and 74 percent is less than at lower concentrations, presumably due to an interaction between the particles. The broken lines cover that part of the curves for which there are no experimental data, and so represents an extrapolation. The assumption has been made that the attenuation changes smoothly with changing concentration.

RESULTS

The ultrasonic absorption was measured at frequencies of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 megacycles per second in sediments composed of three grades of marine sand, washed free of vegetable and soluble matter, and placed in fresh water. The results are shown in Figure 6.

The curve, A, shows the absorption in coarse sand containing particles ranging in diameter from 350 to 650 μ. The mean particle size determined from the measurement of a large number of particles was approximate 450 μ. The absorption in this sediment was too high to be measured at frequencies above 2 megacycles per second.

The curve, B, is for a finer sand containing particles of size from 70 to 300 μ in diameter and having an average size of 180 μ. The absorption here was too high to measure at 3.0 megacycles per second and above this frequency.

The curve, C, is for a still finer sand containing particles from 60 to 180 μ and with a mean particle size of 120 μ. The absorptions were much lower for this sand than for the other sediments, but at 6 megacycles per second they were no longer measurable indicating that the upward trend of the curve continues. These particles are very similar in size to the glass spheres used.

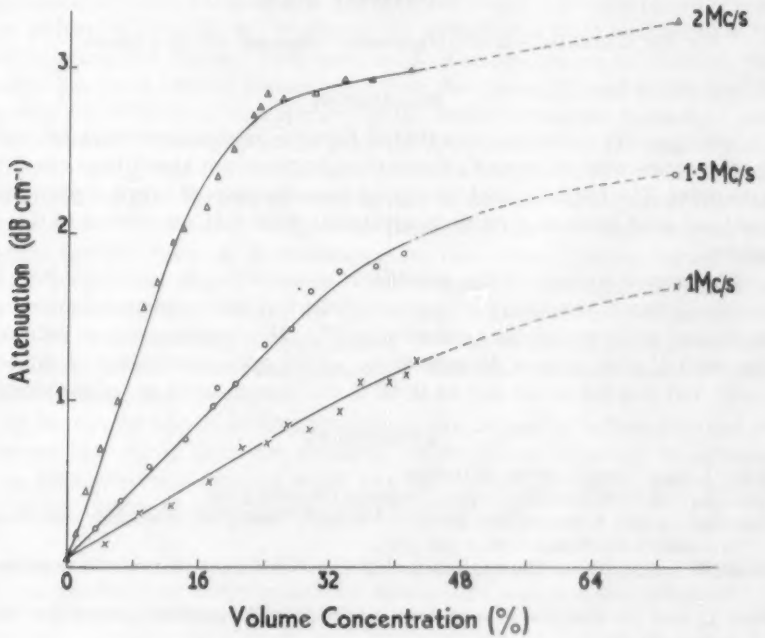

FIG. 5. Variation of attenuation with concentration in a sediment.

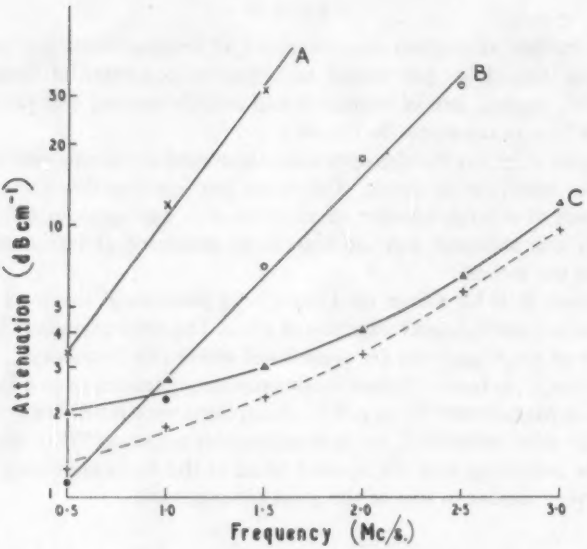

FIG. 6. Attenuation in natural sediments—comparison with glass spheres.

CONCLUSIONS

A comparison of curve C with that of Figure 4, results from which are reproduced as crosses below curve C, shows that the ultrasonic absorptions are of the same order. This indicates that taking the mean diameter of irregular particles in a natural sand leads to a result in agreement with that for spheres of this diameter.

The general increase of the acoustic attenuation (α) in sediments with frequency (f) was in accordance with expectations, but the experimental evidence is insufficient to determine the exact relationship. The measurements in sediments composed of glass spheres do indicate an approximate relationship of the form $\alpha = kf^4$, but this law is not obeyed in all of the natural sands so far examined.

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GEOPHYSICS, VOL. XXII, NO. 4 (OCTOBER, 1957), PP. 829–841, 11 FIGS.

ELECTRICAL RECORDER FOR SEISMIC DATA*

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ABSTRACT

A method of making multitrace seismic records using electrically sensitive paper is described. The record is immediately available for use without any type of processing. A disk carrying wire brushes on its periphery is revolved with its axis parallel to the direction of the motion of the electrical paper. The paper is pulled under the scanning disk and is shaped so that brushes remain in contact with it. Short electrical pulses are fed to the brushes to produce a number of traces composed of closely spaced dots. The position of the dots is determined by the time of occurrence of the pulses. This time is a function of the amplitude of the seismic signal. Timing lines are placed on the record by feeding a series of dots to all brushes. Provision is made to count down and emphasize the fifth and tenth timing lines. A system of multiplexing is used to employ each brush on many traces and thus reduce the rotational speed of the rotating disk. This recorder has proved its usefulness in reproduction of magnetically recorded seismic data.

INTRODUCTION

The use of magnetic recording in seismic exploration has brought about problems in displaying magnetically recorded seismic data in some useful form. The magnetically recorded seismic data has to be converted to a visual record of some type at least at two different locations. The seismic data must be checked in the field to insure that the field equipment and field techniques are satisfactory. This display has much simpler requirements than that normally used in the final interpretation of the data. The operator of the magnetic recorder in the field must know if the equipment is operating properly, if the noise level is satisfactory, and if the shot is of proper size and has been placed at the optimum depth. It is therefore important that the field operator be able to monitor the output of the magnetic recorder rapidly since the speed of operation of the crew depends upon how fast the operator can make decisions as to the next course of action for the crew. On the other hand, when the magnetic data is brought to an interpretation office, the records must be reproduced in a precise form so that computations can be made. It is also important that the display be done as cheaply and conveniently as possible because magnetically recorded data may produce many different seismic records upon playback.

If the display system is time consuming, the amount of information the interpreter can obtain from the magnetic playback system would be reduced. There are a number of systems which may be used for monitoring in the field or for the production of records suitable for interpretation.

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Photographic Oscillograph

One of the best known display systems which has been used for many years is the photographic galvanometer oscillograph. This oscillograph is at a high stage of development, is reliable, and gives high quality seismic records. However, the photographic processing of records is expensive, inconvenient and time consuming. The record must be carefully developed and fixed or it will deteriorate with time. Processing, in the field, is particularly difficult because of the space and time limitations. The geophysical industry has made many attempts in the past to improve or eliminate the photographic process.

Desirable Characteristics of Display Method

A survey made of the various methods for displaying seismic recordings resulted in certain specifications for such equipment as follows:

1) the recording should be rapid, taking no longer than the time to run through the magnetic tape or drum;
2) the recording should not require additional processing;
3) the frequency response should be equal to or better than the standard galvanometer elements;
4) the recording should be rectilinear and have no distortion;
5) the recording should be multitrace and the traces should be able to cross each other;
6) the system should be able to record timing lines similar to those used on seismic records;
7) the record should be made on a permanent medium and should not deteriorate with time;
8) the recording medium should be reasonable in cost.

Medium for Permanent Recording

An investigation of many of the currently available recording media showed that the electrically sensitive paper, called Teledeltos, has many of these advantages. This paper was developed by Western Union Telegraph Company for facsimile use. The paper has three layers. The top layer consists of a thin gray coating. The middle layer consists of a black electrically conductive paper. The bottom layer consists of a thin conducting layer of aluminum paint. If an electrical current is passed from the top layer through the paper to the conducting back layer, the current burns off the gray coating and exposes the black paper underneath. This produces a black line on a gray background.

Other Applications of Permanent Recording

Although the specifications for a desirable display system were determined from the requirements needed for the reproduction of seismic records, a display system which would meet these specifications has many other applications. These applications might include recording of well logs, the readout of analog computers and recording of telemetered data of various types.

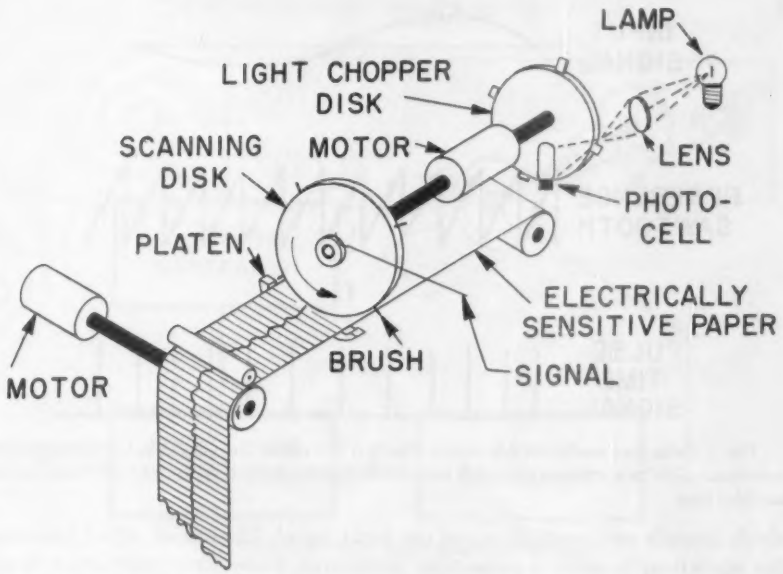

FIG. 1. Single channel Electrograph. The traces and timing lines are formed by closely spaced dots produced electrically by brushes carried on the edge of a rotating disk.

PRINCIPLE OF OPERATION OF A SINGLE CHANNEL ELECTROGRAPH

A recorder employing this electrically sensitive paper is called the *Electrograph*. To understand its principle of operation, consider first a single trace recorder as shown in Figure 1. A number of wire brushes are mounted around the periphery of a rotating disk. The brushes are drawn in contact across the surface of the paper in the direction perpendicular to the motion of the paper. The paper is formed into a section of a cylinder by a metal platen underneath the paper. The radius of the curvature of the paper is the same as the radius of a circle formed by the tips of the brushes so that they remain in contact with the paper. The brushes are spaced around the disk with the separation between the brushes slightly greater than the width of the paper. Only one brush will be in contact with the paper at any one time. The brushes are connected together electrically and the circuit is brought out through a slip ring. The platen serves as a ground return for the brush current.

As each brush crosses the recording paper, at some point on the paper an electrical pulse of short duration is passed from the brush through the paper to the platen. The time of occurrence of this pulse determines the position of a dot on the paper. The dots are made so close to each other that they merge into a line.

The input signal is used to control a series of pulses, the time of occurrence of

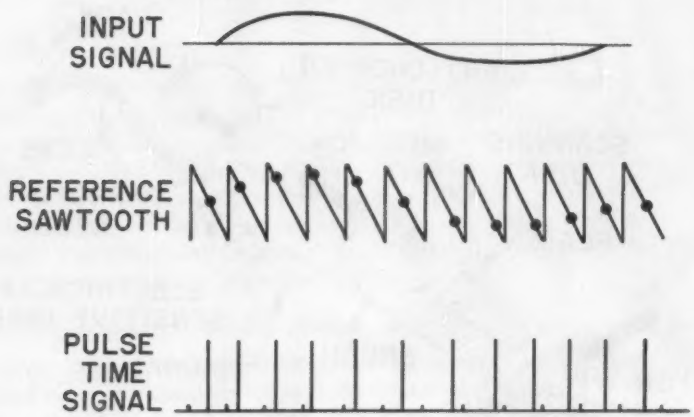

FIG. 2. Pulse time modulator waveforms. The first line shows the input signal. The comparison of the input signal to a reference saw-tooth voltage and resulting pulse-time signal are shown on second and third lines.

which depends on the amplitude of the input signal. The device, which performs this operation, is called a pulse time modulator. Pulse time modulation is accomplished by comparing the amplitude of the incoming signal with a high frequency saw-tooth voltage. An electronic circuit is arranged to give a short pulse when the amplitude of the input signal is exactly equal to the instantaneous amplitude of the saw-tooth voltage. Since both positive and negative signals are to be recorded, the signal voltage must be biased with respect to the saw-tooth voltage. The bias is arranged so that with zero signal voltage the bias will equal one-half of the saw-tooth voltage. If the input signal voltage is zero, the pulse time modulated pulse will consist of a series of equally spaced pulses occurring at a time corresponding to half way distance along the slope of the saw-tooth voltage. If the input signal is positive, the pulse will occur earlier than the pulse for zero signal voltage. Likewise, if the input signal is negative, the pulse will occur later. Referring to Figure 2, the shift in time of the pulse with respect to the reference saw-tooth voltage is shown. During the interval identified by the linear portion of the saw-tooth voltage, a wire brush is crossing the recording paper. Thus, the variation in the time of occurrence of the pulse becomes a similar variation of position of the dot with respect to the edges of the recording paper.

A block diagram of a single channel Electrograph is shown in Figure 3. The pulse time modulator converts the input signal into a series of pulses whose time of occurrence is varied in accordance to the amplitude of the input signal.

A power amplifier is used to amplify the pulses to a sufficiently high voltage to mark the recording paper.

The saw-tooth voltage is generated by a saw-tooth generator which is synchronized with the rotation of the disk carrying the brushes. The saw-tooth is

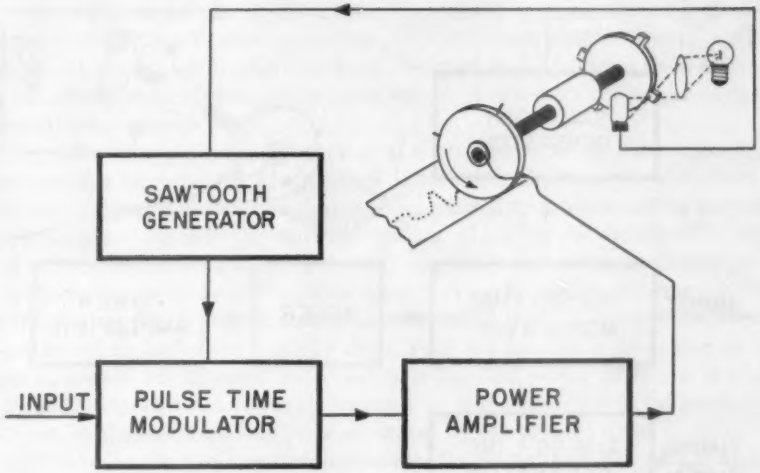

FIG. 3. Block diagram of single channel Electrograph.

initiated each time one of the brushes crosses the edge of the paper. The synchronism is controlled by a toothed wheel which interrupts a light beam. The interrupted light is converted into electrical pulses by a photocell. These pulses are amplified and used to initiate the saw-tooth voltage. The toothed wheel has the same number of teeth as the number of wire brushes on the rotating disk.

PRINCIPLE OF TIMING LINE GENERATION

Timing lines are simultaneously recorded on the Teledeltos paper. These are similar to the timing lines on a conventional seismic record. A block diagram showing a single channel Electrograph with timing lines is given in Figure 4. The lines are formed by a series of timing line pulses applied to the wire brushes simultaneously with the pulses which produce the trace.

The timing line generator furnishes a burst of high-frequency square wave pulses whose onset is determined by an external timing signal such as a tuning fork or a timing signal recorded on the magnetic tape. The duration of the burst of pulses is equal to the time required for a brush to travel across the Teledeltos paper. The frequency of the square wave pulses is sufficiently high so that the individual dots cannot be visually resolved on the record. This line will have a maximum tilt determined by the paper travel during the time required for the brush to travel across the paper. This tilt can be made negligible in the practical instrument. The timing line pulses are added to the time modulated pulses in an adder circuit placed between the pulse time modulator and the power amplifier.

An electronic counting circuit is used to lengthen each fifth and tenth pulse burst to form fifth and tenth timing lines. Two rows of dots are made on fifth and

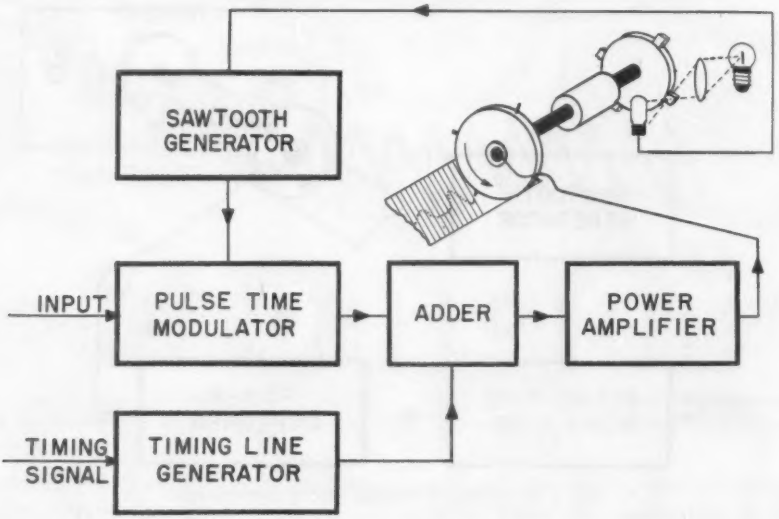

FIG. 4. Block diagram of single channel Electrograph with timing lines.

three rows of dots are made on tenth lines by lengthening the pulse duration (see figure 5). This widening does not impair the accuracy of the front edge of the timing lines.

THE PRINCIPLE OF OPERATION OF MULTIPLE TRACE ELECTROGRAPH

Seismic information is usually displayed as a multitrace record. The recording principles used in a single trace unit can be used to produce a multiple trace record. However, a serious practical problem exists in the multiple trace recorder. In such a device, in order to preserve the recording quality, the dot repetition rate cannot be decreased. It is also necessary to keep the rotational speed of the brush disk to a practical value. It is possible to make a multiple trace recording with only one brush contacting the recording paper at a time. Since the number of dots per second for each trace must remain constant, the velocity of the brushes across the paper will increase in proportion to its width. If a large number of traces spaced at intervals commonly employed in photographic oscillograph are required, a wide paper must be used. To achieve the dot repetition rate the single brush disk must be either large or it must rotate at a high speed. As an example, a fourteen trace recorder would require a brush disk 4 feet in diameter rotating at 3,600 rpm or a 7 inch brush disk rotating at 25,000 rpm. Either makes the construction of such an instrument impractical. This problem can be solved by the use of multiple brushes and a rapid electronic switching technique. In such a system the brushes are switched so that each brush is used several times as it crosses the paper.

An additional feature of a multiple trace record in seismic work is that the traces should be able to cross each other. This provides a compact record in which the character of the individual traces can be more easily followed from one trace to the next. The cross-over of the traces can be obtained by the proper design of the switching system.

In order to simplify the discussion of a multiple channel Electrograph, an example of a four channel Electrograph is next considered. A block diagram of this arrangement is shown in Figure 6. Four pulse time modulators are required. Their outputs pass into the electronic switch which will be described in detail below. After the proper switching the four outputs are passed through four power amplifiers. The pulses from the power amplifiers are applied to the four slip rings on the rotating brush disk. The scanning disk has 16 brushes. Every fourth brush is connected to one of the four slip rings. Four brushes are on the paper at one time with each one of them connected to a different power amplifier. A single saw-tooth generator is used for all channels. It is synchronized to the brush disk rotation by the synchronizing pulse generated by the toothed wheel interrupting a light beam in the same manner as used in the single trace Electrograph. The brush switching sequence is shown in Figure 7 for a four channel Electrograph in which each trace is allowed trace-to-trace excursion.

The four brushes marked A_1, A_2, A_3, and A_4 are connected together and wired

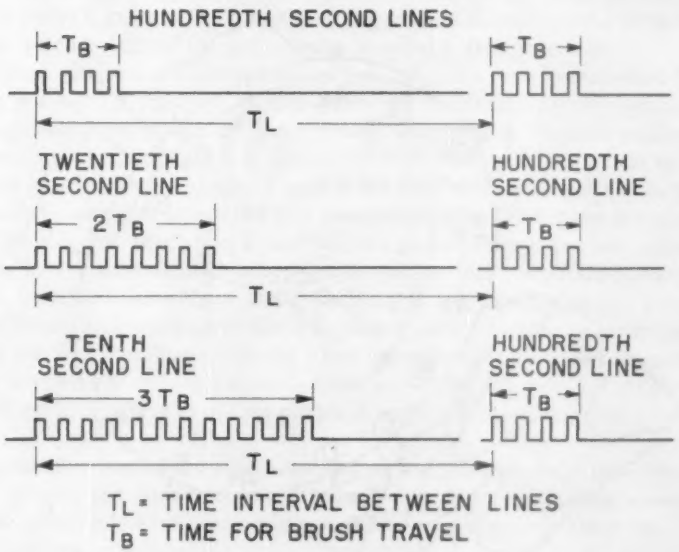

FIG. 5. Timing line waveforms. Timing line pulse trains for hundredth, twentieth and tenth second lines.

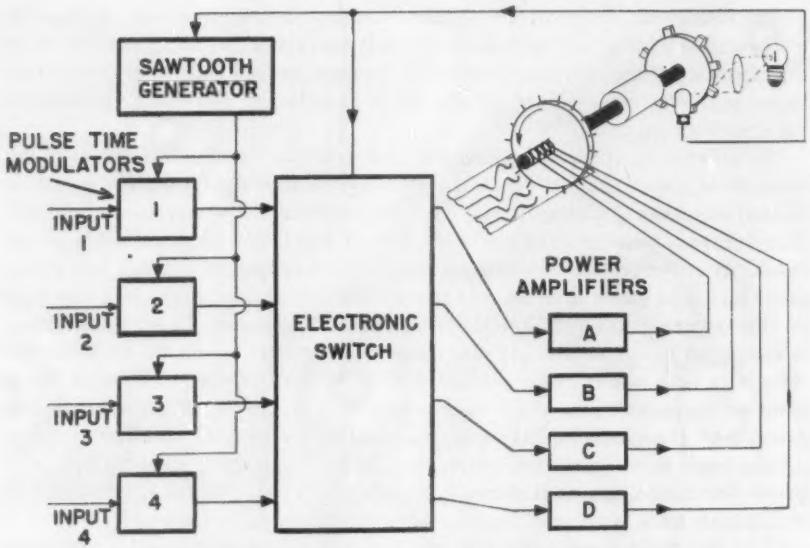

FIG. 6. Block diagram of four channel Electrograph.

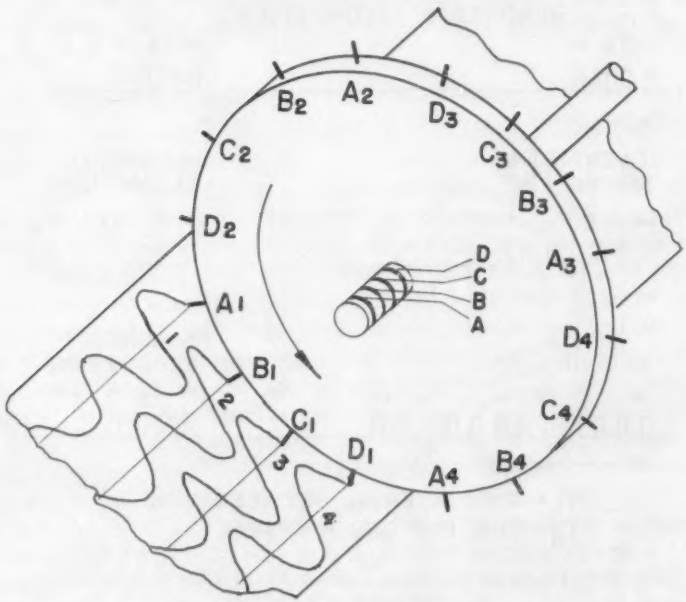

FIG. 7. Brush switching is used to reduce rotational speed of the brush disk.

to the commutator slip ring marked A. The brushes marked B_1, B_2, B_3, and B_4 are connected together and wired to the commutator slip ring marked B, etc. Brushes A_1, B_1, C_1, and D_1 will each place a dot on traces 1, 2, 3, and 4, respectively, within one saw-tooth voltage cycle. When brush C_2 moves to the proper position, it will make a dot on trace 1, brush D_2 on trace 2, while brush A_1 makes a dot on trace 3, and B_1 on trace 4. As the brush disk rotation is continued, brush A_2 will make a dot on trace 1, B_2 on trace 2, C_2 on trace 3, and D_2 on trace 4. This pattern of switching will continue. It can be seen that in this case any one wire brush has to travel only a distance equal to two trace spaces during the time required to generate one dot. If this system were not switched, the single brush would have to travel four trace spaces in the time required to generate one dot. The peripheral speed of the brushes is thus reduced by a factor of two and each brush is used twice as it crosses the paper. The dots forming trace 1 can occur anywhere between the edge of the paper and the undeflected position of trace 2. The dots forming trace 2 can occur anywhere between the undeflected positions of trace 1 and trace 3. The dots forming traces 1 and 2 may crossover in the region between the undeflected positions of traces 1 and 2.

Rapid rate of switching is required for this application. The switching system used in the Electrograph consists of a large number of controlled vacuum tubes connected in a matrix pattern. The individual tubes may be turned on by a controlling pulse. The controlled tubes are arranged so that the time-modulated pulse will not pass through the tubes unless a controlling pulse is present. Such a tube is called a gated tube. The controlling pulse is called a gating pulse and the device which generates the gating pulse is called a gate generator.

A block diagram of the electronic switching system for a four channel Electrograph is shown in Figure 8. A gate generator is actuated by the synchronizing pulse generator which also initiates the saw-tooth voltage. The gate generator has two outputs. Each output is a square wave which is positive in time sequence.

The gated tubes are arranged so that the time modulated pulse does not pass through the amplifier unless the gate pulse is positive. During the period of time in which the first gate pulse is positive, the gated tubes in the first column are active. The time modulated pulse from modulator No. 1 is passed to output circuit A, from modulator No. 2 to output circuit B, from modulator No. 3 to output circuit C and from modulator No. 4 to output circuit D. During the second gate period the second column of gated tubes are active. The pulse from modulator No. 1 is passed to output circuit C, from modulator No. 2 to output circuit D, from modulator No. 3 to output circuit A and from modulator No. 4 to output circuit B.

A provision has been made to ensure that the first gate pulse is positive when brush A is in the region to record trace No. 1. If the gate pulse generator is allowed to begin in wrong sequence, trace No. 1 may appear on the record in trace No. 3 position.

The timing line generator is similar to the one used in the single channel Electrograph, except the duration of the burst of pulses is made equal to the travel

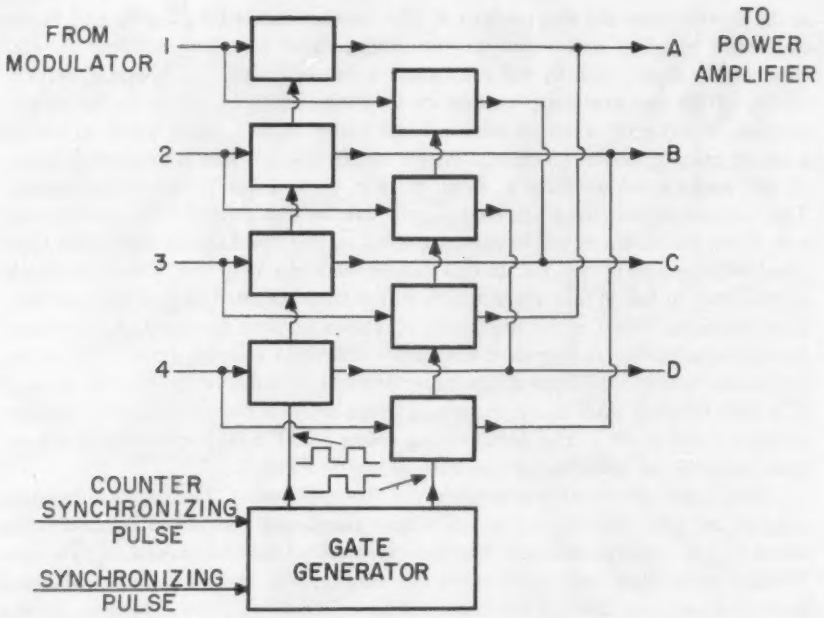

FIG. 8. Block diagram of the electronic switching system showing the use of gated tubes and the gate generator.

time of the brush between adjacent traces. The timing line pulses are added to the pulse time modulator pulses simultaneously in the same manner as used in the single channel Electrograph.

FOURTEEN TRACE ELECTROGRAPH

The present Electrograph has fourteen traces with each trace having a maximum excursion to the undeflected position of the adjacent traces. The fourteen trace Electrograph is an expansion of the four trace Electrograph above.

Fourteen pulse time modulators, fourteen adder circuits and fourteen power amplifiers are used, one for each trace. One saw-tooth generator and a time line generator are used for the entire unit. The gate generator produces seven outputs each consisting of a square wave which is positive in sequence for one-seventh of the time. The electronic switch matrix uses fourteen gated tubes for each of the seven gate periods utilizing a total of 98 gated tubes. Each brush is used seven times as it crosses the paper, thus reducing the peripheral speed by a factor of seven. The scanning disk rotates at 3,600 rpm. Each trace is formed by 2,500 dots per second. The timing lines are formed by 50,000 dots per second.

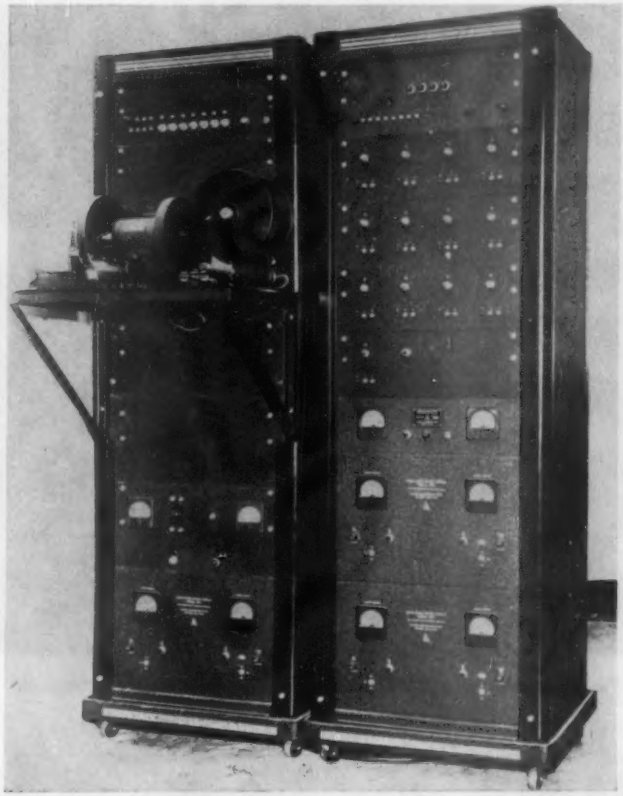

FIG. 9. Physical appearance of complete fourteen channel Electrograph.

A typical five-second seismic record will be formed by over 350,000 dots. The records are made on four inch Teledeltos paper supplied in 1,000-ft rolls.

The low frequency response is -3 db at 3.5 cps. The maximum useful high frequency response is not limited by the circuitry but is by a minimum number of dots which adequately describes a trace. With a pulse repetition rate of 2,500 dots per second, a 200 cycle per second wave can be reproduced satisfactorily.

The physical appearance of the Electrograph is shown in Figure 9. The mechanical portion of the Electrograph is mounted on a shelf in front of the left cabinet. The electronic circuits and power supplies are housed in the two cabinets. Figure 10 shows closeup of the brush disk with its driving motor, the synchronizing toothed wheel and its optical system, the paper drive system, paper supply roll and the platen which shapes the paper.

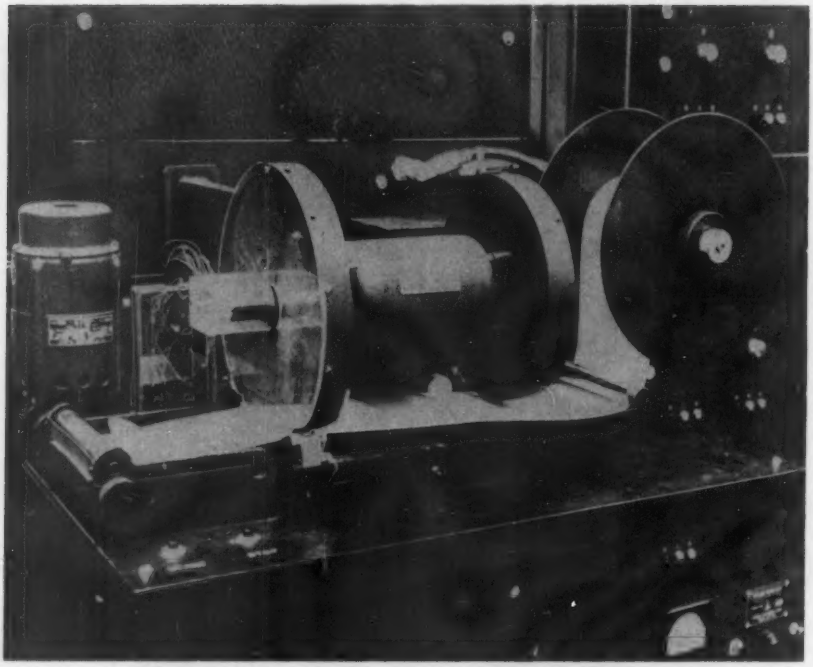

FIG. 10. Physical appearance of the mechanical portion of the Electrograph.

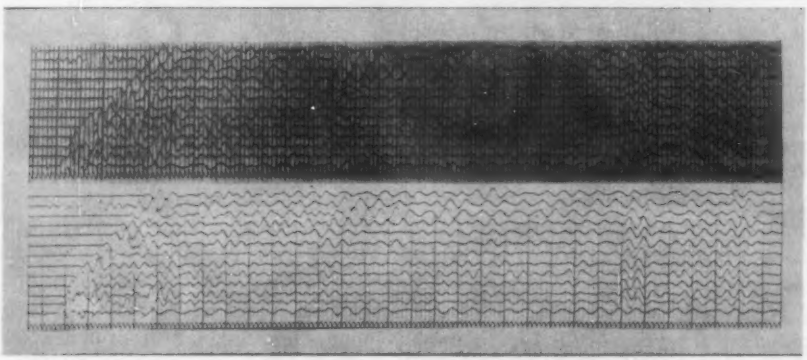

FIG. 11. Comparison of Electrograph and photographic oscillograph records. The first twelve traces on each record are the result of playback from a magnetic tape through a filter. The thirteenth trace is an unfiltered playback which includes the time break. The fourteenth trace is the timing signal which is used to control the timing lines on the records.

An example of a seismic record produced by the Electrograph is shown in Figure 11. A photographic oscillograph record obtained from the same magnetic tape is included for comparison. The first twelve traces of each record are the result of playback from a magnetic tape through a filter. The thirteenth trace is an unfiltered playback which includes the time break. The fourteenth trace is the timing signal which is used to control the timing lines on the records.

The Electrograph has been used continuously at Pan American Research Center to reproduce magnetic recorder records with satisfactory results.

As the record is made at the same rate as the data are fed into the Electrograph and no subsequent processing is needed, it enables playbacks to be made of the magnetically recorded seismic data at a rate which could not be achieved using the conventional photographic oscillograph.

GEOPHYSICS, VOL. XXII, NO. 4 (OCTOBER, 1957), PP. 842–847, 5 FIGS.

SURFACE AMPLITUDES OF REFLECTED BODY WAVES*

L. KNOPOFF,† R. W. FREDRICKS,† A. F. GANGI,† AND L. D. PORTER†

ABSTRACT

The components of the surface motions of a plane free surface are computed for the incidence of plane body waves.

INTRODUCTION

In many problems of seismology, we may wish to study wave motions in the absence of the earth's surface. The practicability of placing detectors on the surface of the earth or on the surface of a seismic model, suggests the need for methods for the conversion of the amplitudes as measured on surfaces into actual body wave amplitudes. Because of the familiar $P-SV$ interaction at reflecting surfaces, the motion at a free surface does not describe directly the incident body wave motion. We provide here the corrections to be applied to surface motion data to produce the actual body wave amplitudes.

The calculation is elementary and for special cases has been carried out in the literature. Jeffreys (1926) has calculated the correction data for Poisson's ratio $\sigma = .25$. Gutenberg (1944) provides similar data for $\sigma = .215, .239, .250, .273$. With the advent of accurate amplitude measurements on seismic models having unusual values of σ, correction data should be available for greater ranges of σ. In this paper we compute, for a number of values of Poisson's ratio, the components of surface motion for incident plane P and SV body waves.

INCIDENT P WAVES

Let plane P-waves of unit amplitude be incident upon a free surface from within an elastic, homogeneous half-space. Let the angle of incidence be θ.

Applying the boundary conditions concerning the vanishing of the normal and shear stress at the surface, we obtain for the amplitude of the vertical component of the motion the expression

$$\tfrac{1}{2} U_{zp} = \frac{\sin\theta}{\cos 2\phi \tan\theta + 2\sin^2\phi \tan 2\phi} = \frac{\sin\theta}{R(\theta, \phi)} \tag{1}$$

and for the horizontal component the expression

$$\tfrac{1}{2} U_{xp} = \frac{\sin\theta \tan 2\phi}{R(\theta, \phi)} \tag{2}$$

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Publication No. 85, Institute of Geophysics, University of California.
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TABLE I

VALUES OF $\cos 2\phi \tan\theta + 2\sin^2\phi \tan 2\phi$

		σ						
		0.4	0.3	0.25	0.2	0.1	0.05	0.0
	0°	0	0	0	0	0	0	0
	10°	0.1760	0.1765	0.1769	0.1772	0.1779	0.1783	0.1786
	20°	0.3610	0.3654	0.3683	0.3714	0.3777	0.3807	0.3836
	30°	0.5656	0.5807	0.5917	0.6035	0.6285	0.6412	0.6535
	40°	0.8044	0.8414	0.8700	0.9041	0.9808	1.0212	1.0625
θ	50°	1.1031	1.1690	1.2354	1.3185	1.5280	1.6056	1.7860
	60°	1.5196	1.6049	1.7321	1.9142	2.4635	2.8501	3.3397
	70°	2.2342	2.2459	2.4775	2.7739	4.1516	5.5019	7.8193
	80°	4.2624	3.6413	3.7156	4.1114	6.9682	11.7176	32.221
	85°	8.0156	6.1242	5.7071	5.7378	8.7816	16.3551	131.307

where

$$\frac{\sin\theta}{\sin\phi} = \frac{\alpha}{\beta};$$

α and β are the velocities of compression and shear waves respectively. The factors $\frac{1}{2}$ have been introduced to normalize the peak amplitude of the vertical component to unity for normal incidence. The "Rayleigh" denominator of equations (1) and (2), $R(\theta, \phi)$, occurs with such frequency that a table of values is provided in Table I. Curves of the above two functions are presented in Figures 1 and 2 as functions of the angle of incidence θ and for values of Poisson's ratio $0 \leq \sigma \leq \frac{1}{2}$ where

$$\sigma = \frac{\alpha^2 - 2\beta^2}{2(\alpha^2 - \beta^2)}.$$

INCIDENT SV WAVES

Let the plane waves again be incident upon a free surface from within an elastic, homogeneous, isotropic half-space. Let the wave motions, in this case, be polarized SV and let the angle of incidence be ϕ. Applying the boundary conditions, the vertical component of the motion is

$$\tfrac{1}{2} U_{zz} = \frac{\sin\phi \tan 2\phi}{R(\theta, \phi)} \tag{3}$$

while the horizontal component is

$$\tfrac{1}{2} U_{zx}^{*} = \frac{\cos\phi \tan\theta}{R(\theta, \phi)}. \tag{4}$$

At the critical angle the z-component of the motion vanishes identically. However there are complications associated with these motions at angles greater

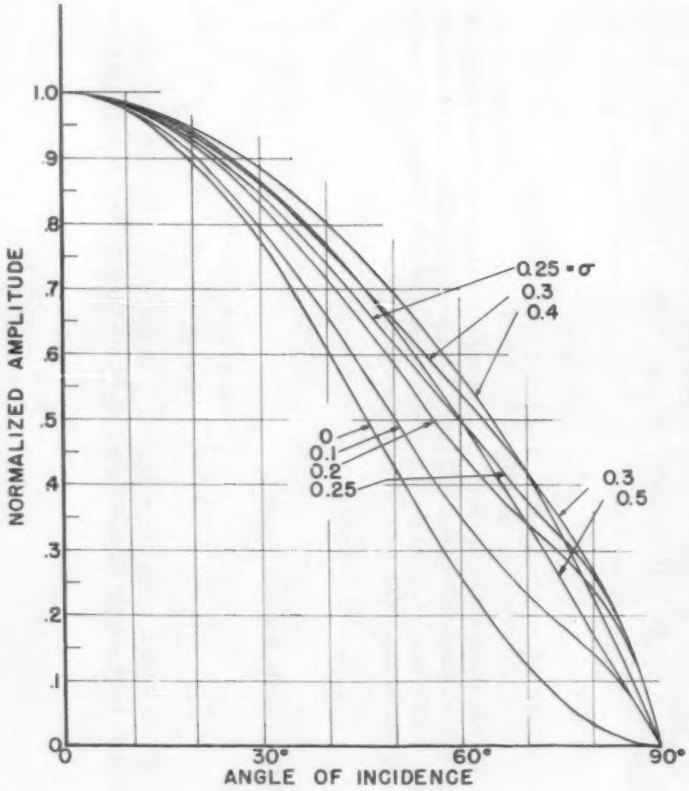

FIG. 1. Normal component of motion for incident *P*-waves.

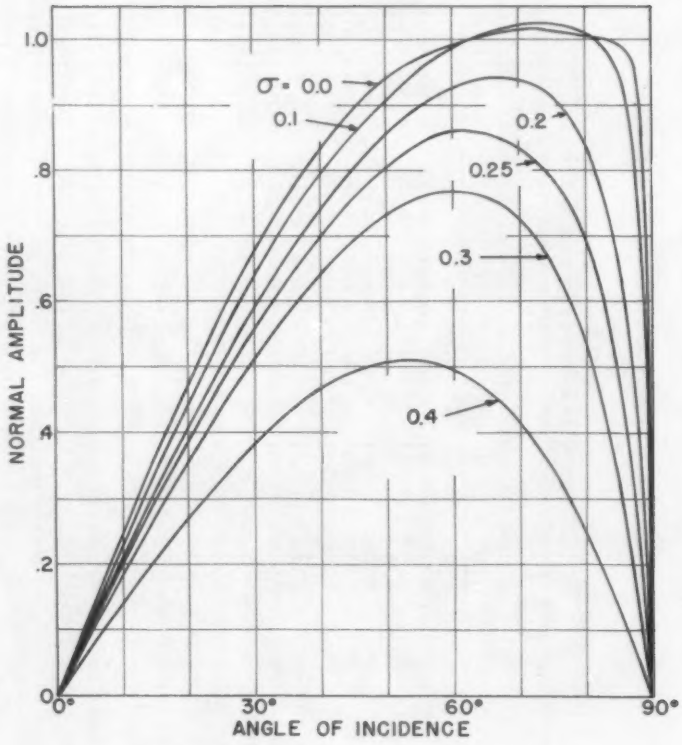

FIG. 2. Horizontal component of motion for incident *P*-waves.

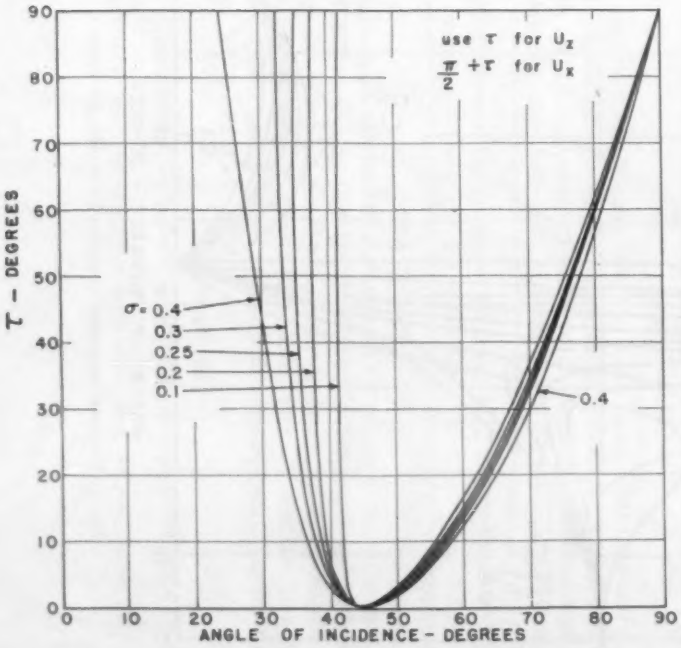

FIG. 3. Phase angles for *SV* incident at angles exceeding the critical angle.

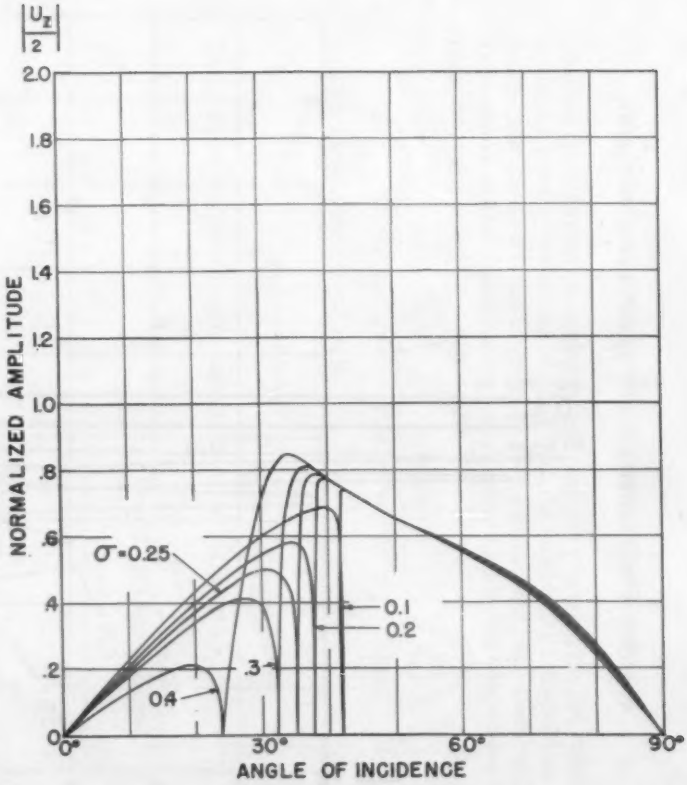

FIG. 4. Normal component of motion for incident *SV*-waves.

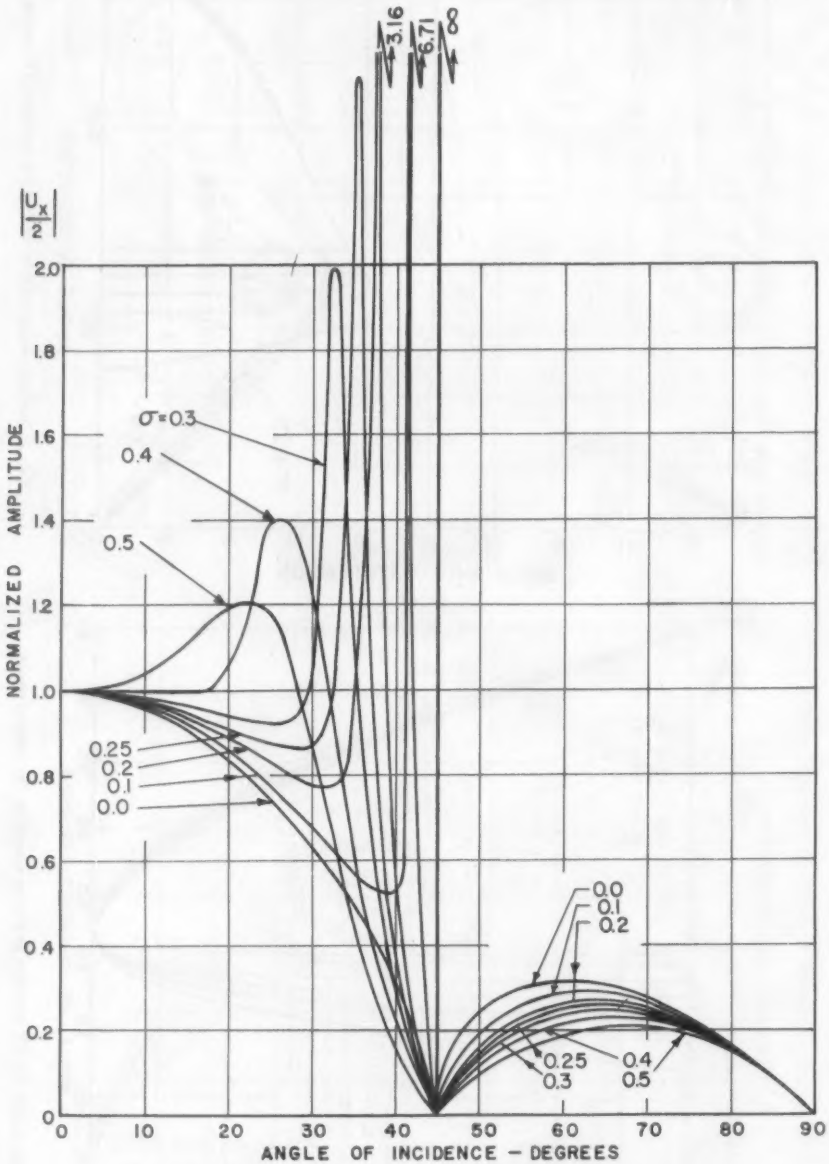

FIG. 5. Horizontal component of motion for incident *SV*-waves.

than the critical angle. At angles greater than the critical angle, the reflected P becomes a surface "wave" out of phase with the incident SV; the incident SV is totally reflected as SV but it too undergoes a phase shift. The computation at angles above critical is most conveniently treated by allowing θ to become imaginary. At angles below the critical angle,

$$\tan \theta = \frac{\sin \phi}{(\beta^2/\alpha^2 - \sin^2 \phi)^{1/2}}. \tag{5}$$

At angles above the critical angle,

$$\tan \theta \rightarrow i \tanh \theta' = \frac{i \sin \phi}{(\sin^2 \phi - \beta^2/\alpha^2)^{1/2}}. \tag{6}$$

Then, above the critical angle, equations (3) and (4) become

$$\tfrac{1}{2} U_{ss} = \tfrac{1}{2} \left| U_{ss} \right| e^{i\tau} = \frac{\sin \phi \tan 2\phi \, e^{i\tau}}{(\cos^2 2\phi \tanh^2 \theta' + 4 \sin^4 \phi \tan^2 2\phi)^{1/2}} \tag{7}$$

$$\tfrac{1}{2} U_{ss} = \tfrac{1}{2} \left| U_{ss} \right| e^{i\tau} = \frac{i \cos \phi \tanh \theta' e^{i\tau}}{(\cos^2 2\phi \tanh^2 \theta' + 4 \sin^4 \phi \tan^2 2\phi)^{1/2}} \tag{8}$$

where

$$\tan \tau = \frac{\tanh \theta' \cos 2\phi}{2 \sin^2 \phi \tan^2 \phi}. \tag{9}$$

By inspection of equations (7) and (8), it can be seen that the phase angles of U_{ss} and U_{ss} differ by 90° at angles above the critical. Hence, a calculation of the phase shift in, say, U_{ss} compared with that of the incident wave suffices for the determination of the phase shift in both waves. This phase shift is given in Figure 3.

The magnitudes of the quantities $\frac{1}{2}U_{ss}$ and $\frac{1}{2}U_{ss}$ are presented in Figures 4 and 5 as functions of the angles of incidence ϕ.

ACKNOWLEDGMENTS

The authors are indebted to the Amerada Petroleum Corp., Atlantic Refining Co., Cities Service Oil Co., Continental Oil Co., Gulf Research and Development Co., Magnolia Petroleum Co., Phillips Petroleum Co., Shell Development Co., Stanolind Oil and Gas Co., Sun Oil Co., The Texas Co., and the Texas Instruments Co. for their support of the Seismic Scattering Project of the University of California.

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Jeffreys, H., 1926, Reflexion and refraction of elastic waves: Mon. Not. Roy. Astron. Soc., Geophys. Suppl., v. 1, p. 321–334.

GEOPHYSICS, VOL. XXII, NO. 4 (OCTOBER, 1957), PP. 848-869, 14 FIGS.

GRAVITY PROSPECTING FOR CHROMITE DEPOSITS IN CAMAGUEY PROVINCE, CUBA*

W. E. DAVIS,† W. H. JACKSON,‡ AND D. H. RICHTER‡

ABSTRACT

Detailed gravity surveys were made in Camaguey Province, Cuba, as part of a systematic exploration program conducted by the U. S. Geological Survey on behalf of the General Services Administration to locate deposits of refractory-grade chromite. During the period August 4, 1954, to April 5, 1956, a total of 41,921 gravity stations were established in nine areas embracing about 11.8 square miles in the Camaguey chromite district. The results of the surveys were used in connection with information obtained in geologic investigations to guide exploratory drilling.

Gravimeters with low scale constants were used in making measurements sufficiently accurate to delimit anomalies as small as 0.5 gravity unit. The measurements were made over 20×40 and 30×60 meter grids and at stations 20 and 30 meters apart, respectively, along intermediate traverses in anomalous areas. Gravity differences were determined by single observations at individual stations, observing base stations hourly, and re-observing a few stations to check drift and accuracy of measurement. About 11 percent of the stations established had to be re-run because of errors in closure, microseisms, and instrument trouble.

A large number of anomalies were found and evaluated according to geology, areal extent, and gravity relief. Depths to disturbing hypothetical bodies were computed to guide drilling. Test drilling of 106 positive anomalies revealed that ten features overlie deposits of chromite and 89 occur over bodies of other dense materials. The other seven anomalies were not explained by materials found in drilling. Core drilling on five of the chromite deposits revealed about 236,000 tons of chromite. An additional estimated 12,000 tons are contained in three deposits which were not blocked out. No estimate was made of the tonnage in two small deposits.

INTRODUCTION

Gravity surveys were made in connection with an exploration program conducted by the U. S. Geological Survey in the Camaguey chromite district, Cuba, to locate deposits of refractory-grade chromite. Detailed gravimeter measurements were made in nine areas (Fig. 1) covering about 11.8 square miles, where previous geologic studies (Flint and others, 1948) indicated conditions favorable for the occurrence of large deposits of chromite.

The feasibility of using the gravity method in prospecting for these deposits was tested in surveys conducted by the Gulf Research and Development Company (Hammer, 1945a; 1945b) in development work done in the district by the Bethlehem Steel Company in 1942. The results of these surveys showed that gravity anomalies of +0.5 gravity unit or more in magnitude were associated with the deposits, but only a comparatively small number of the anomalies were caused by bodies of chromite; most of the anomalies were caused by masses of other dense materials and by changes in soil thickness. It was concluded that in

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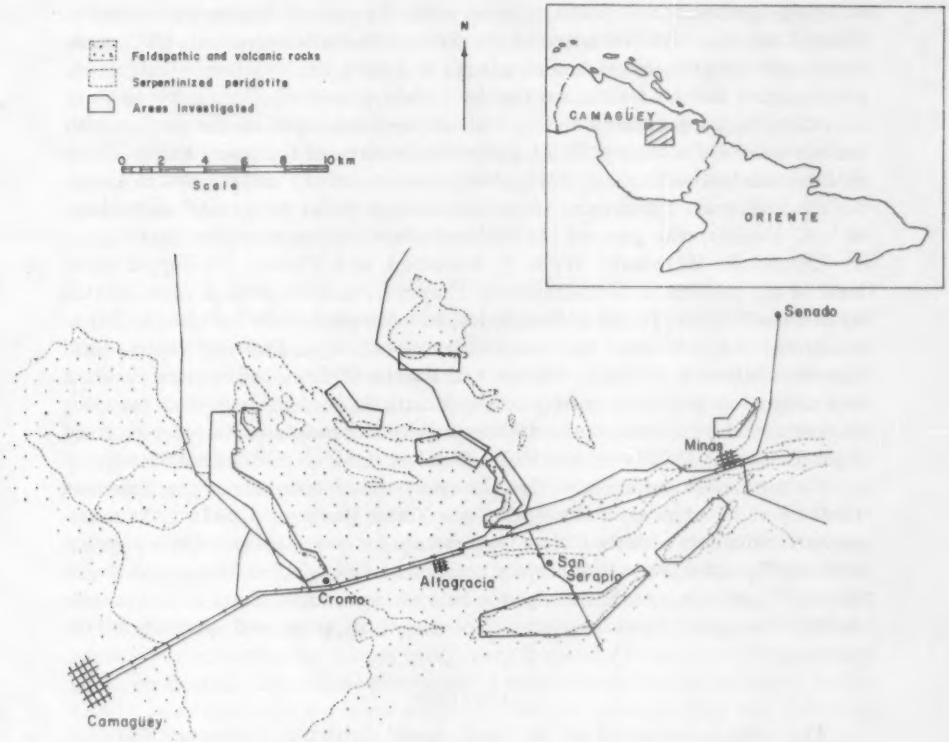

FIG. 1. Index map showing location of areas investigated in the Camaguey chromite district, Cuba.

an exploration program gravity surveys could be used advantageously to delineate areas underlain by dense materials and, thereby, serve to localize exploratory drilling.

The information obtained in previous geologic and gravity investigations indicated that detailed geologic mapping in connection with gravity surveying would be helpful in guiding the survey work and evaluating the gravity features. Therefore, the plan of exploration was to locate bodies of dense materials by means of gravity surveys, evaluate the corresponding anomalies on evidence revealed by detailed geologic mapping, test the most favorable gravity features by drilling, and determine approximately the quantity of chromite in any deposits found. Because a large area would have to be mapped in order to find substantial reserves, the gravity work was directed toward obtaining maximum coverage accurately with as few repeat observations as possible.

The project was undertaken in behalf of the Emergency Procurement Service, General Services Administration of the United States Government. Field work was done during the period August 4, 1954 to April 5, 1956 by Geological Survey geophysicists and geologists, assisted by Cuban personnel. During the peak of operation, 10 U. S. citizens and 13 Cubans were employed on the project with headquarters in Camaguey. W. D. Johnston, Jr. directed the investigation. Delos E. Flint was instrumental in getting the project underway and assisted in directing the field work. The gravity surveys were made under the general supervision of L. C. Pakiser, who planned the field procedure and inspected the data.

Richard R. McDonald, Willie T. Kinoshita, and Thomas N. Hopper made most of the gravimeter measurements. They were assisted during a few months by Martin F. Kane, Jorge M. Hernández, and Alfredo Pulido. Dionisio A. Bueno conducted the horizontal and vertical control surveys. Roy M. Shuler, Raúl Celestino Miranda, Pablo A. Calván, and Evelyn G. Langford reduced the data and assisted in preparing gravity maps. Martin S. Tischler assisted in mapping the geology and supervising the drilling. Advice and assistance was also received from Messrs. T. P. Thayer and P. W. Guild of the U. S. Geological Survey.

We are pleased to acknowledge the assistance of members of the *American Embassy* and *Foreign Operations Mission to Cuba*, Havana, in making the necessary arrangements with the Cuban Government for undertaking the investigation and in efficiently processing project equipment and supplies through customs. We wish especially to acknowledge the help of Mr. Paul A. Tate, U. S. Consular Agent, Camaguey, in obtaining local personnel, supplies, and quarters for the project.

LOCATION

The areas investigated are in the chromite district of Camaguey Province, near the towns of Altagracia, Cromo, and Minas (Fig. 1). They lie along the edges of a broad open plain or savannah that surrounds most of the farming land in the district. The surface of the country is relatively flat except for a few scattered hills, mine dumps, and excavations. Sparse brush, bunch grass and scattered stubby palms cover the savannah. More luxuriant vegetation, consisting mainly of large patches of marabu, royal palms and other trees, grows along the edges of the farming land.

GEOLOGY AND CHROMITE DEPOSITS

The chromite deposits are in serpentinized peridotite and dunite near their contact with feldspathic rocks and/or rocks of volcanic origin. The serpentinized rocks underlie the savannah and contain feldspathic rocks, mainly gabbro, troctolite, and anorthosite, as well as the chromite. Many of the feldspathic masses are not well exposed but can be delineated by small outcrops, float, and a characteristic flora. Almost everywhere the peridotite and dunite are covered by a thin layer of lateritic soil.

Most of the deposits in the district lie in a zone about half a mile wide that runs along the serpentinized rock-feldspathic and/or volcanic rock contact. The deposits are irregular lenticular and tabular masses ranging in size from small pods to masses several hundred feet in length containing 200,000 tons or more. Most of the chromite deposits are oriented so that the long axis parallels the strike of the nearest contact between feldspathic or volcanic rocks and the serpentinized peridotite. The chromite in the deposits varies from a massive coarse-grained ore containing minor amounts of silicate impurities to fine-grained chromite disseminated in the peridotitic host rock.

FIELD OPERATIONS AND COMPUTATIONS

Application of the gravity method in prospecting for chromite deposits in the Camaguey chromite district depends fundamentally upon the density contrast between the chromite and the surrounding country rock. The difference in density between the chromite contained in commercial deposits of the district and the country rock, which is serpentinized peridotite and dunite, is about 1.5 grams per cubic centimeter. This density contrast is sufficient for chromite masses lying at commercially exploitable depths to cause positive gravity anomalies of magnitudes more than 0.5 gravity unit (0.05 milligal). The feldspathic rocks in the serpentinized peridotite and dunite have an average density of about 2.7 grams per cubic centimeter, which provides a sufficient density contrast with respect to the serpentinized rocks to cause anomalies of much the same size and magnitude as the chromite. Similar anomalies also are created by density contrasts between parts of the serpentinized masses which vary in density from 2.2 to 2.8 grams per cubic centimeter. Therefore, gravimeter measurements can be expected to delineate areas underlain by dense materials, but the areas must be test drilled to determine if the materials are chromite.

As more than two-thirds of the ore mined in the district came from deposits 45 to 60 meters long, containing 90,000 tons or more, the exploration was planned to search for deposits of this size. The station density of a 20×40 meter grid was considered to be of sufficient detail to detect most of the anomalies associated with these deposits. However, it would be necessary to check anomalous measurements and map the gravity features more in detail before undertaking exploratory drilling. As the gravity work progressed, a 30×60 meter grid was found to be satisfactory for reconnaissance purposes and was used to obtain greater areal coverage.

The grid pattern was laid out by means of a transit and tape survey, which provided accurate control for locating claim corners and drill holes. Stations were staked at intervals of 20 or 30 meters along traverses spaced 40 or 60 meters apart situated at right angles to a base line paralleling the general trend of the serpentinized rock contact. Additional gravity stations were laid out for detailed work where anomalous conditions were found in the reconnaissance gravity mapping. In the areas where the 20×40 meter grid was used, intermediate traverses were

laid out with stations at 20-meter intervals forming 20×20 meter grids over the gravity features; over the center of a few anomalies, stations were located at intervals of 10 meters. In areas investigated on a 30×60 meter grid basis, detailed stations were staked forming a 15×15 meter grid over the gravity anomalies. The elevations of stations, referred to an arbitrary base, were determined to less than 1/10 of a foot by leveling. The horizontal and vertical control was established by a surveyor and five assistants hired locally.

Reconnaissance geologic investigations were made in advance of the control survey to determine the location of the base line and length of the gravity traverses. Following the layout work, the geology was mapped in detail, using the grid as a base. The contact between rock types was located as accurately as possible along each traverse and interpolated between the traverses. Small isolated rock exposures not crossed by the traverse lines were also included in the mapping.

Two Worden gravimeters, having scale constants of 0.7172 and 0.7856 gravity units per scale division, were used in making the gravity surveys. These instruments have a reading dial range of about 80 divisions and can be read to 1/10 of a dial division. The scale constants of the meters were checked periodically by observing the gravity difference between two survey stations that differed by about 36.5 gravity units. No appreciable change in the scale constants was noted during the course of the work.

Gravity base stations were established as the work progressed using the standard looping method. The gravity value of each base was determined from an average of five measurements differing by no more than 0.3 gravity unit. The gravity differences between grid stations were determined by making single observations at individual stations and observing a base station at intervals of one hour. During the initial run of stations from a base in the morning and after lunch, a repeat observation was made at the base station within 45 minutes. As an additional check on the drift of the meter, and the accuracy of the meter operator's reading, a repeat reading was made of at least one station of each previous run from the base.

One gravimeter was used regularly in making reconnaissance measurements and the other was used in detailing anomalies and making re-runs of misclosures. The meter crews consisted of an operator, a recorder, and one assistant. The meters were transported between stations by hand and, during readings, were shaded by umbrellas that also served as wind shields. For ease and rapidity in making measurements, two tripods eleven inches in height were used with each instrument. While one tripod was in use at a station in making an observation, the other was set at the advance station by the recorder. Approximately 0.28 square mile was mapped with the gravimeter during the first two months, mainly to establish control. After this preliminary period, the mapping progressed at an average rate of about 0.55 square mile per month until November 15, 1955, when

measurements were undertaken on a 30×60 meter grid basis. Thereafter, an average of about 1.06 square miles was mapped per month.

The drift of the meters was adjusted from a linear-function-of-time graph and lines which failed to close by 0.5 scale division (0.39 gravity unit) or more were re-run. About 11 percent of the 41,921 stations established during the course of the work had to be re-run because of misclosures, microseisms, and instrument trouble. The precision attained in making the gravimeter readings is indicated by the difference in measurement found at 3,136 re-observed stations (Fig. 2): The average difference between the repeat measurements is 0.17 scale division (0.13 gravity unit); 53.5 percent of the repeat readings differ by 0.1 scale division (0.08 gravity unit) or less; 89.9 percent differ by 0.3 scale division (0.24 gravity unit) or less; and only 2.3 percent of the measurements differ by more than 0.5 scale division (0.39 gravity unit). These data indicate that the probable error of a single observation is about 0.10 scale division (0.08 gravity unit).

After adjusting the gravimeter readings for drift, standard methods were used in reducing the data to obtain Bouguer and residual gravity values. A correction of 5.54 gravity units per kilometer was applied to compensate for the change in gravity with latitude. A combined elevation correction of 0.62 gravity unit per foot, based on an experimentally determined rock density of 2.5 grams per cubic centimeter, was used in reducing the measurements to a common datum. Terrain corrections were not applied to the data because of the flat topography. Residual gravity values were determined by means of the nine-point second-derivative method (Henderson and Zietz, 1949), using 80- and 120-meter squares for the 20×40 and 30×60 meter grids, respectively. In some of the anomalous areas, the residuals were smoothed graphically.

The Bouguer gravity values were plotted in profile form immediately after reduction to locate errors caused by erroneous elevations and meter readings at individual stations. The profiles also were used for control in removing regional effects graphically in parts of the mapped areas and in studying and interpreting the gravity features, most of which were not completely isolated by the nine-point residual method. Bouguer and residual gravity maps were prepared on a geologic base to determine the relationship of the gravity features with known geologic conditions. These maps were used in connection with the profiles to evaluate and select anomalies for detailed mapping and test drilling.

The positive gravity anomalies were classified for investigation according to their relationship to outcrops of feldspathic rocks. Most of the anomalies were grouped in three classes in decreasing order of favorability:

(1) anomalies apparently not related to feldspathic rocks;

(2) anomalies overlying serpentinized rocks but in line with or along the strike of feldspathic outcrops, indicating possible subsurface continuations of the feldspathic bodies; and

(3) anomalies occurring partly over feldspathic outcrops and partly over

serpentinized rocks. The anomalies that occurred entirely over feldspathic outcrops were considered definitely unfavorable and were not mapped in detail.

The anomalies also were studied and classified according to areal extent,

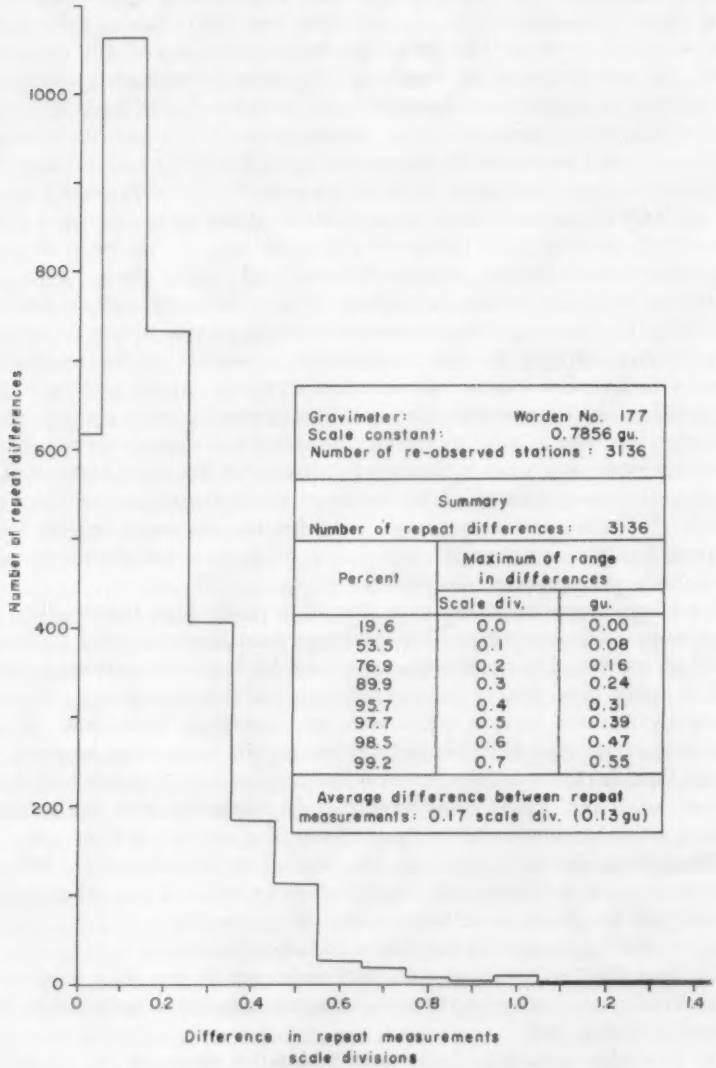

FIG. 2. Frequency-difference curve of repeat gravimeter measurements.

gravity relief, and the theoretical amount of chromite indicated. The features were grouped in three main classes in descending order of importance:

(A) prominent anomalies of more than 0.5 gravity unit magnitude that were shown on more than one traverse profile; this group of anomalies was classified further according to the quantity of chromite indicated,
  (1) more than 90,000 tons,
  (2) 50,000 to 90,000 tons, and
  (3) less than 50,000 tons;

(B) anomalies of magnitudes of about 0.5 gravity unit that were not depicted prominently by the nine-point residual reduction, and were indicative of deep chromite bodies or disseminated chromite deposits, or possibly caused by differential weathering in the country rock or changes in soil thickness; and

(C) anomalies of small areal extent and of magnitudes less than 0.5 gravity unit that could be caused by small deposits of chromite or by density contrasts in near-surface materials, dump materials around mines, or could be the result of the manner in which the residual reduction was made.

Residual gravity maps contoured on intervals of 0.2 gravity unit were prepared of the individual detailed anomalies to determine the locations of test holes. Depths to the top and center of hypothetical disturbing bodies that would cause similar anomalies were computed in terms of chromite and feldspathic rock to guide drilling. Cores were taken in test drilling when dense materials were cut and at the respective computed center depths and/or near the bottom of the holes. Specific gravities of the cored samples were determined to ascertain the source of the anomalies. The chromite bodies found were core drilled to determine the tonnage and to obtain samples of the chromite.

RESULTS

A large number of anomalies with a gravity relief of 0.5 gravity unit or more were found scattered widely over the mapped areas. The significant Bouguer gravity features consisted of prominent closures, noses, and re-entrants occurring along the major contact between serpentinized rocks and feldspathic or volcanic rocks; an increse in the gravity gradient along parts of the contact; a marked difference in the uniformity of gravity contours between parts of the respective areas; broad general gravity highs and lows; and several minor closures and flexures. The major features seem to be associated mainly with masses of feldspathic rocks along the contact and in the serpentinized country rock. Positive residual anomalies flanked by gravity lows are associated with large outcrops of feldspathic rock. The significant anomalies overlie serpentinized rocks near large feldspathic bodies and in parts of the areas where only small masses of dense rock were observed. Many small anomalies occur in dump areas around mine workings. No anomalies of consequence were observed over feldspathic outcrops less

than 10 feet across or over small exposed bodies of disseminated chromite.

Test holes ranging in depth from 27 to 375 feet were drilled on the crests of 106 gravity anomalies. The results of drilling revealed that ten anomalies overlie deposits of chromite, 47 occur over feldspathic rock, 40 are associated with dense parts of the serpentinized rocks, two overlie deposits of magnesite-talc-quartz rock, and seven occur over serpentinized rocks which do not seem to be sufficiently dense to cause variations in gravity. Drilling on five of the chromite deposits revealed about 236,000 tons of chromite, of which 19,000 tons are of the disseminated type. An additional estimated 6,000 tons of shipping grade chromite and 6,000 tons of disseminated chromite are contained in three of the deposits that were not blocked out. No estimate was made of the tonnage in two small chromite deposits.

The tested gravity anomalies do not have characteristic features identifying the materials with which they are associated. Although most of the anomalies caused by chromite are comparatively small and are fairly prominent and regular, many of the anomalies caused by other heavy materials are similar.

Bouguer and residual gravity maps depicting an anomaly over a 24,000-ton chromite deposit discovered by the investigation are shown in Figures 3 and 4. Prior to the investigation, a small amount of chromite was exposed inconspicuously in a shallow prospect pit near drill hole *A*. Additional trenching, after completion of drill holes *A* and *B*, determined the surface extent as shown in the figures. The chromite body extends to a depth of 197 feet, dips steeply to the southwest, and is probably terminated by a fault between drill holes *B* and *E*. The anomaly overlies the main part of the deposit and indicates possible extensions to the west and southwest. The southwest extension was investigated by one test hole that failed to cut chromite in drilling to a depth of 300 feet.

The gravity anomaly associated with the largest chromite deposit found is shown on the Bouguer and residual gravity maps in Figures 5 and 6. The deposit lies very close to an outcrop of troctolite near the northwest end of a large abandoned mine. The chromite body contains approximately 115,000 tons, dips steeply toward the southwest, and comes within ten feet of the surface (Fig. 7). Most of the ore lies below 75 feet and the bottom is between 225 and 250 feet deep. The anomaly is prominent and regular in shape, involves 12 stations, and has a gravity relief of 1.6 gravity units. The position of the anomaly with respect to the outcrop indicated that the feature could be caused by a continuation of the troctolite at depth. However, in view of the absence of an anomaly over the outcrop, it was suggested that this anomaly might be caused by a faulted extension of the mined body to the south.

The largest anomaly found associated with chromite (Fig. 8) embraces 46 stations and has two gravity maxima of 1.4 and 1.5 gravity units respectively. The anomaly overlies an irregular, discontinuous, tabular deposit containing about 72,000 tons of chromite. Near the central gravity maximum, the ore comes within 40 feet of the surface and extends to a depth of 140 feet (Fig. 9). Near the

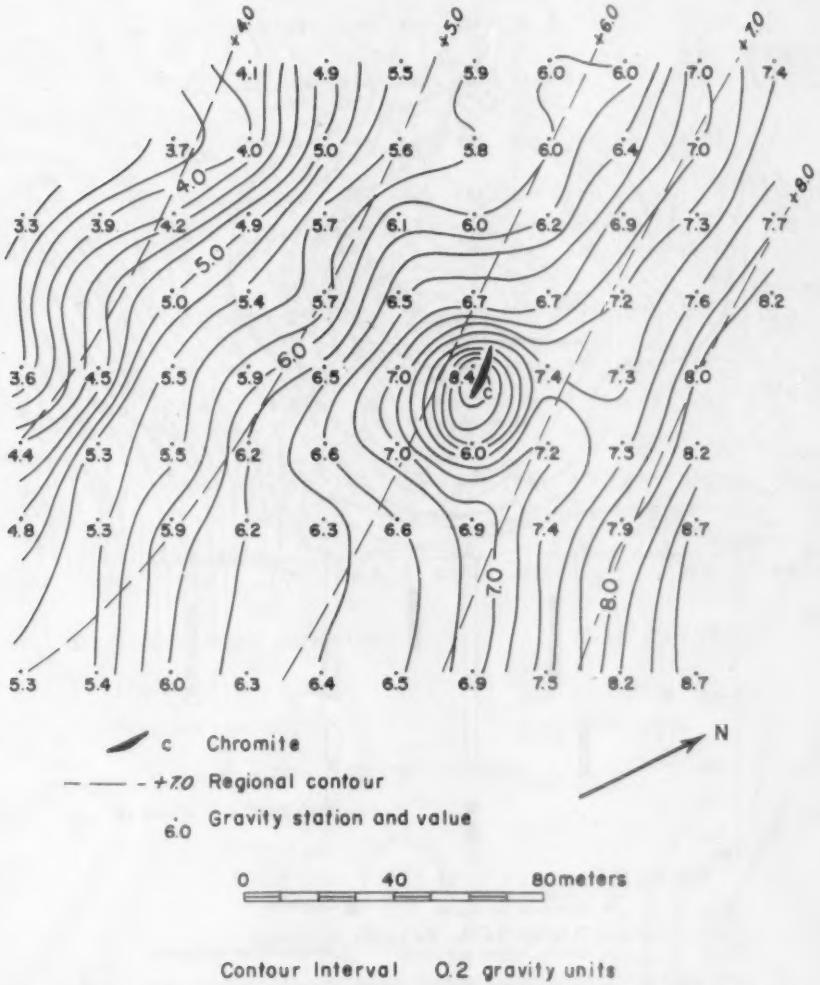

FIG. 3. Bouguer gravity map showing an anomaly caused by a 24,000-ton chromite deposit.

other gravity maximum the ore lies between depths of 76 and 168 feet. A gap in the chromite body is indicated near the center of the anomaly by five holes which failed to cut ore. A small isolated body of chromite, 28 feet thick, underlies the west end of the anomaly.

A residual gravity map showing part of a typical anomaly associated with

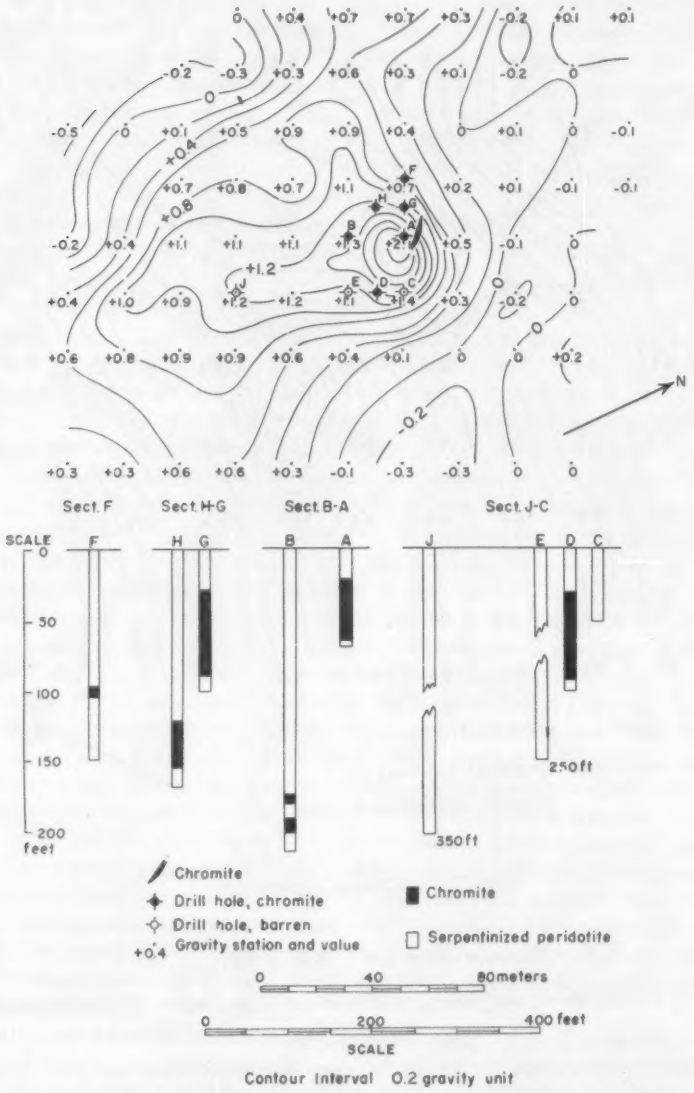

FIG. 4. Residual gravity map showing an anomaly caused by a 24,000-ton chromite deposit, and drill hole sections through the chromite body.

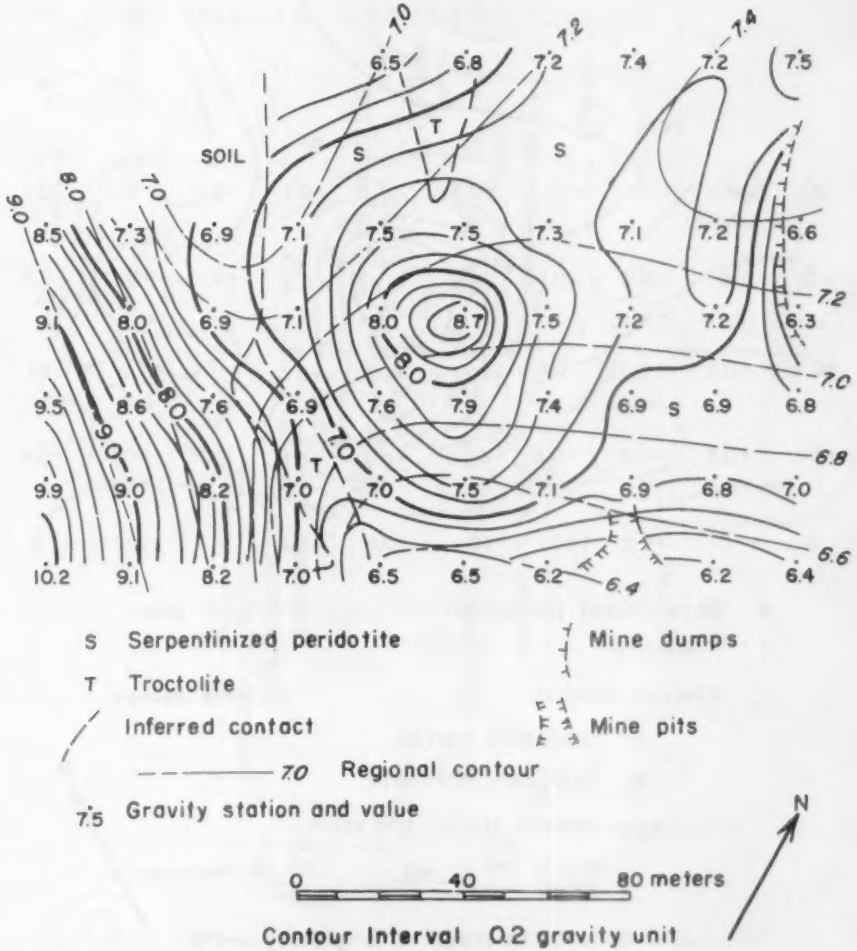

FIG. 5. Bouguer gravity anomaly over a chromite deposit containing 115,000 tons.

dense serpentinized peridotite is shown in Figure 10. The anomaly involves more than 41 stations and has two gravity maxima of 1.2 and 1.3 gravity units respectively. Serpentinized peridotite, which was hard to drill, was found in test holes *A* and *B* located on the gravity maxima. Hole *A* cut hard peridotite at depths between 65 and 248 feet, and samples taken at depths of 115 and 151 feet had a specific gravity of 2.73. Hole *B* went through hard peridotite extending

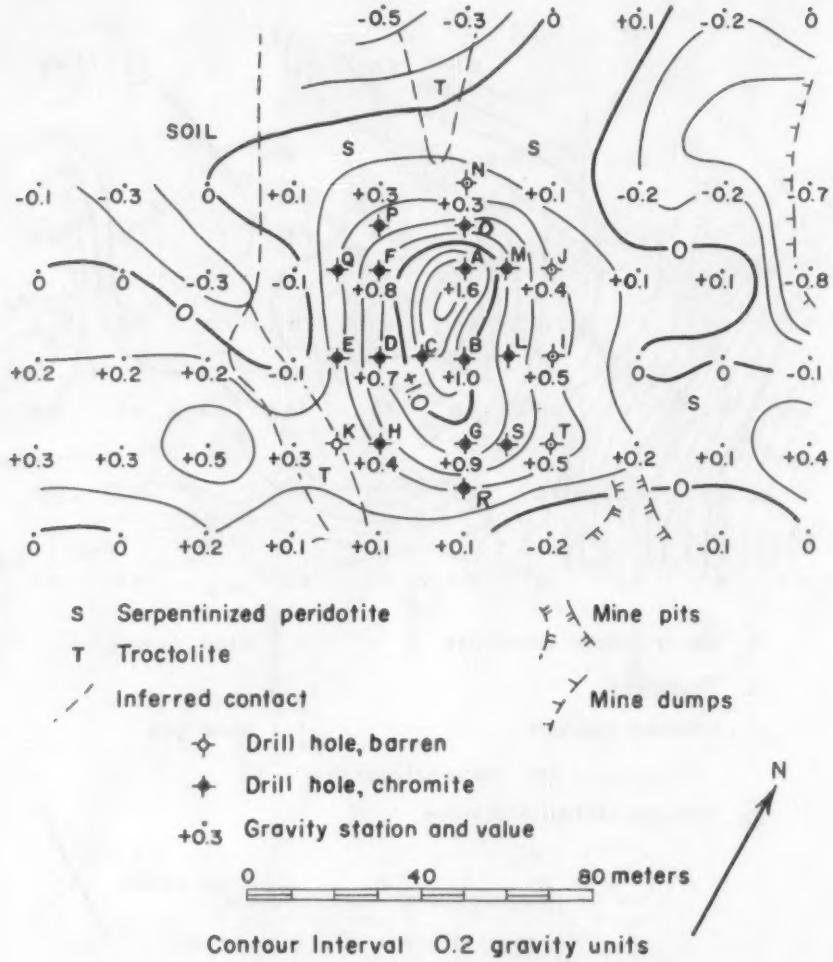

FIG. 6. Residual gravity anomaly over a chromite deposit containing 115,00 tons.

from a depth of 2 feet to the bottom of the hole 150 feet deep. A sample taken between depths of 43 and 45 feet in this hole had a specific gravity of 2.62. In hole C, 100 meters southwest of the anomaly, easy-drilling serpentinized peridotite was found to a bottom depth of 102 feet; a sample taken at depth of 100 feet had a specific gravity of 2.52.

A gravity anomaly caused by a body of troctolite in serpentinized peridotite

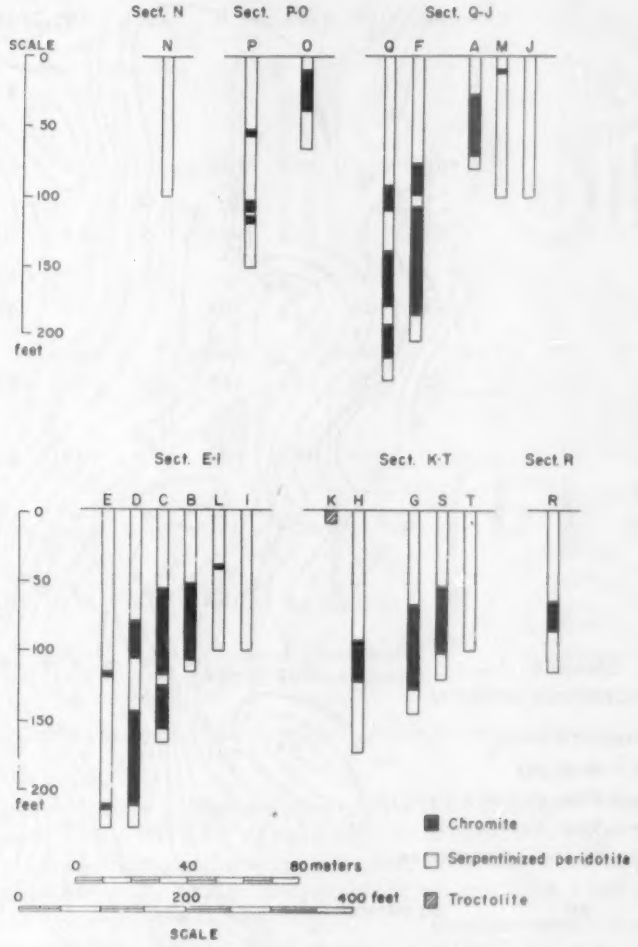

FIG. 7. Drill hole sections through the chromite deposit illustrated in Figure 6.

is shown in Figure 11. Small exposures of chromite near the inferred contact between troctolite and peridotite indicated that part of the anomaly could be associated with a deposit of chromite. Therefore, a test hole was drilled near the central part of the anomaly over peridotite. Troctolite was cut within a few feet of the surface and extended to the bottom of the hole 32 feet deep. A cored sample of the troctolite had a specific gravity of 2.68.

Figure 12 shows a gravity anomaly crossing the contact between gabbro and

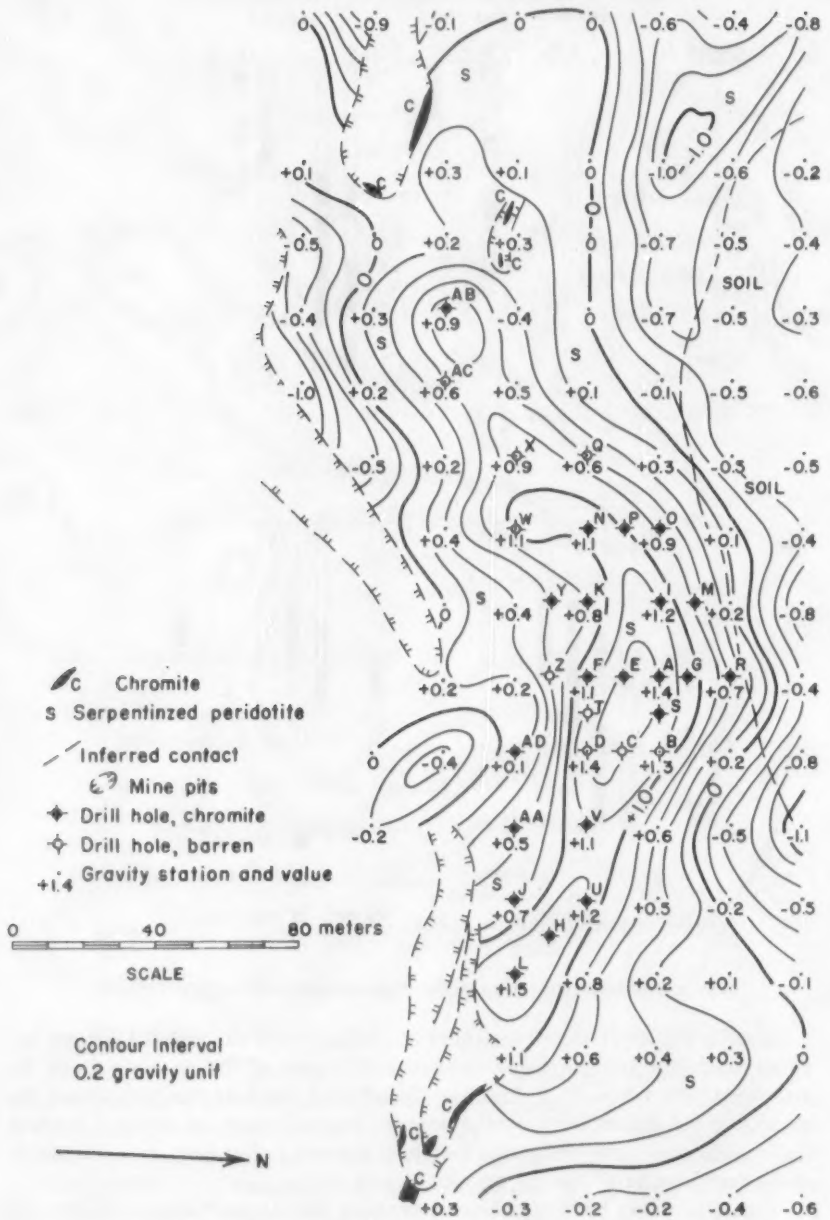

FIG. 8. Residual gravity anomaly over a discontinuous tabular deposit containing 72,000 tons of chromite.

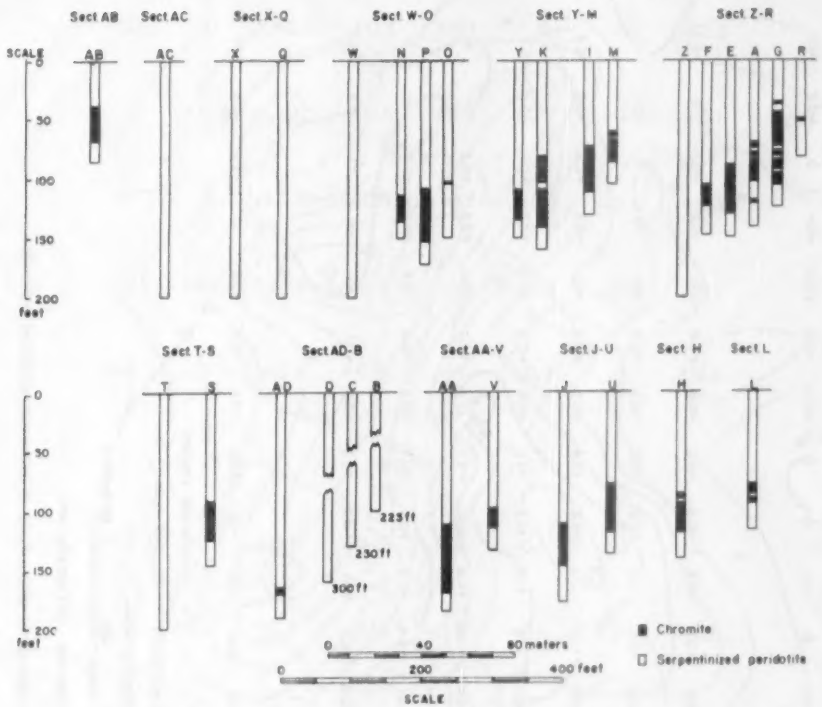

FIG. 9. Drill hole sections through the chromite deposit illustrated in Figure 8.

serpentinized peridotite. The anomaly has a gravity relief of 1.0 gravity unit and embraces 16 stations. A test hole drilled on the crest of the anomaly over peridotite found gabbro between depths of 73 and 97 feet, the bottom of the hole. The anomaly is probably caused by a thicker part of the gabbroic mass, which in part extends under the serpentinized peridotite.

The most prominent anomaly found in mapping is shown in Figure 13. The feature lies in a dump area near a large mine and has a gravity relief of 4.8 gravity units. A test hole 105 feet deep drilled near the center of the anomaly disclosed gabbro between depths 8 and 105 feet. A sample of gabbro taken between depths 100 and 105 feet had a specific gravity of 2.66.

One of the largest anomalies which was drilled is shown in Figure 14. This anomaly embraces more than 140 stations and has a gravity relief of 3.6 gravity units. A hole drilled at the center of the anomaly disclosed rock composed predominantly of a mixture of the minerals magnesite, talc, and quartz, lying between depths of 5 and 100 feet. A sample core taken at a depth 72 feet had a specific gravity of 2.87. The outcrops of ferruginous silica shown may represent the highly weathered surface exposure of this body.

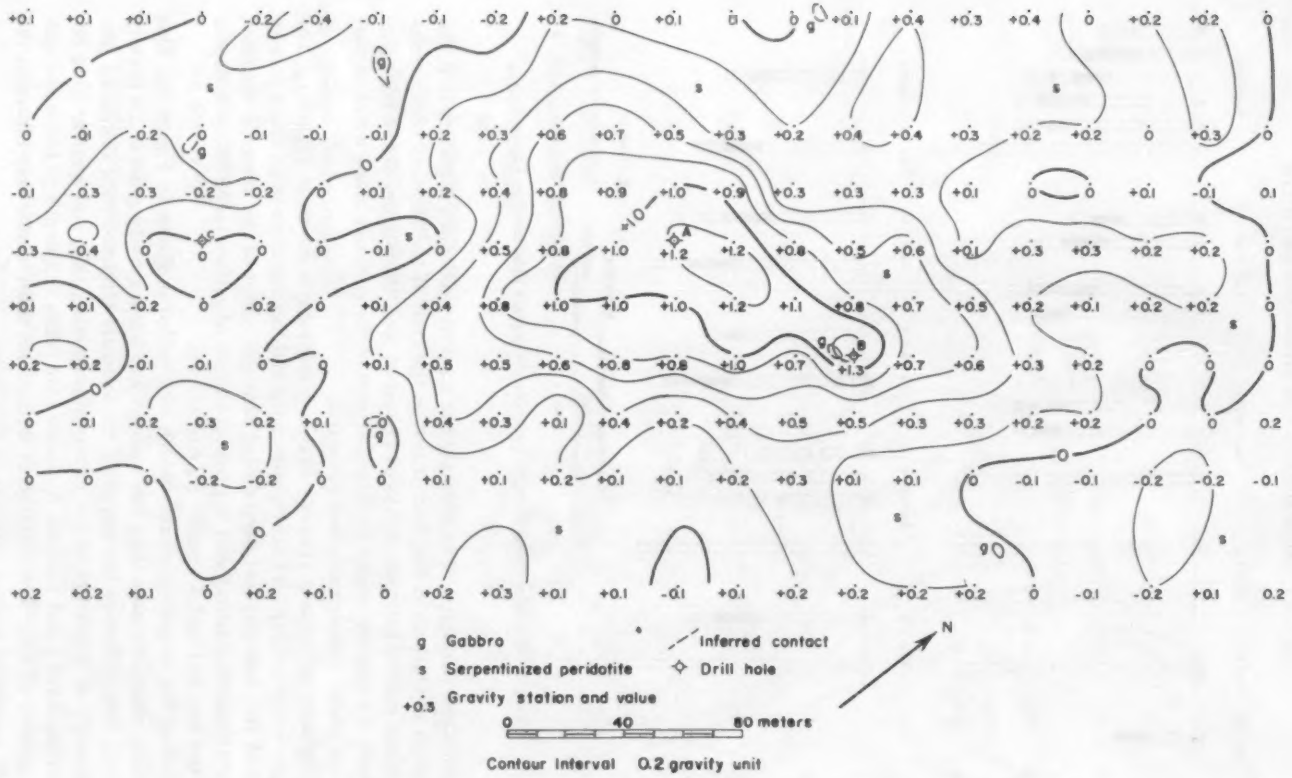

FIG. 10. Residual gravity anomaly associated with a body of dense serpentinized peridotite.

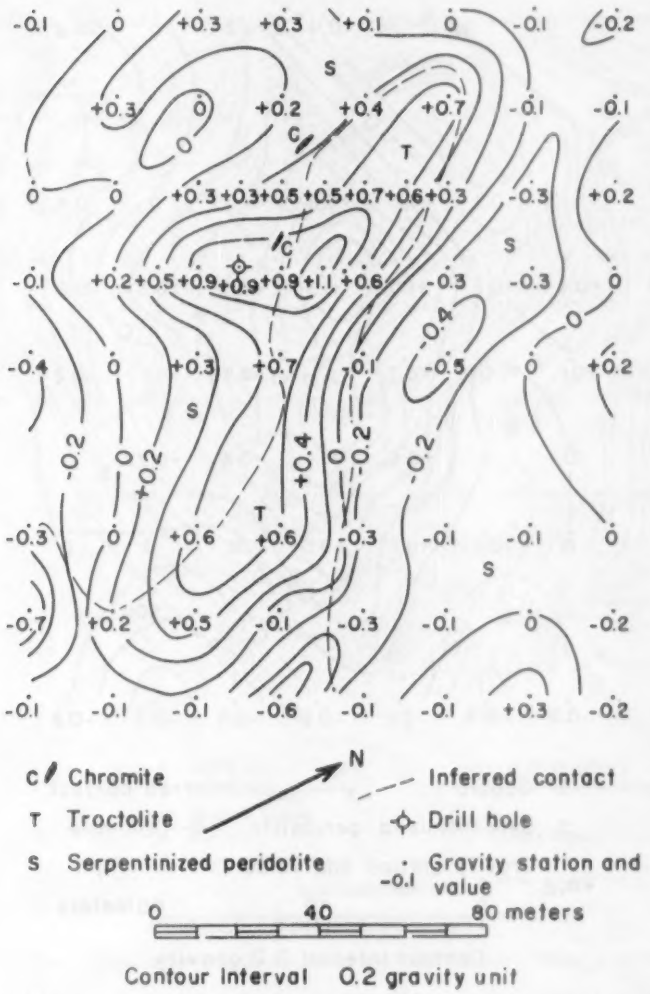

FIG. 11. Residual gravity anomaly caused by troctolite in serpentinized peridotite.

DISCUSSION

The gravity data indicate that under favorable terrain conditions detailed gravimeter surveys, of the precision usually required in searching for mineral deposits, can be carried out successfully using standard field techniques. The accuracy necessary in making measurements can be attained by exercising normal

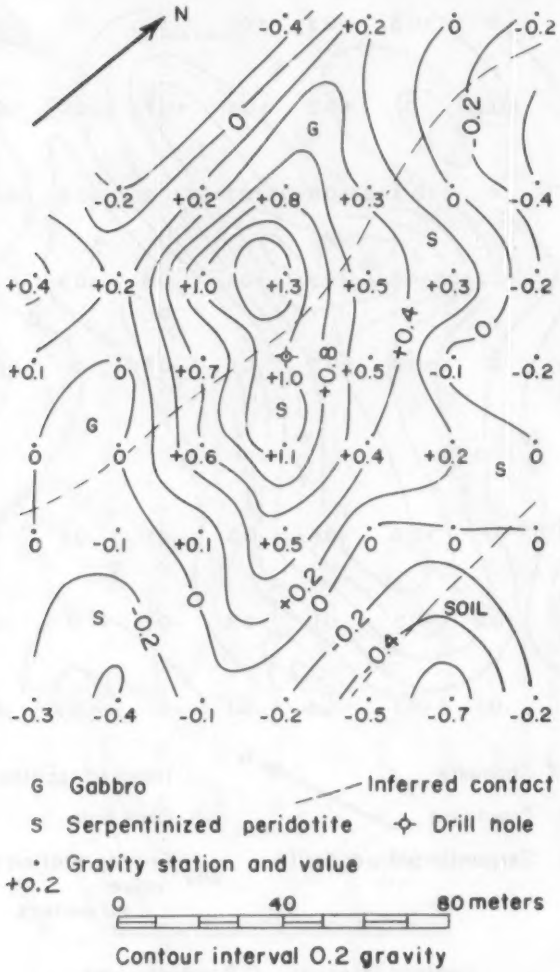

FIG. 12. Residual gravity anomaly overlying the contact between gabbro and serpentinized peridotite.

care in handling and reading the meter, and by frequently checking the instrumental drift through re-observing base stations and a limited number of intermediate stations. Reconnaissance measurements, adequately spaced to detect significant anomalies, followed by close-spaced measurements over anomalous parts will expedite the investigation of large areas.

The investigation reveals the importance of using integrated detailed gravi-

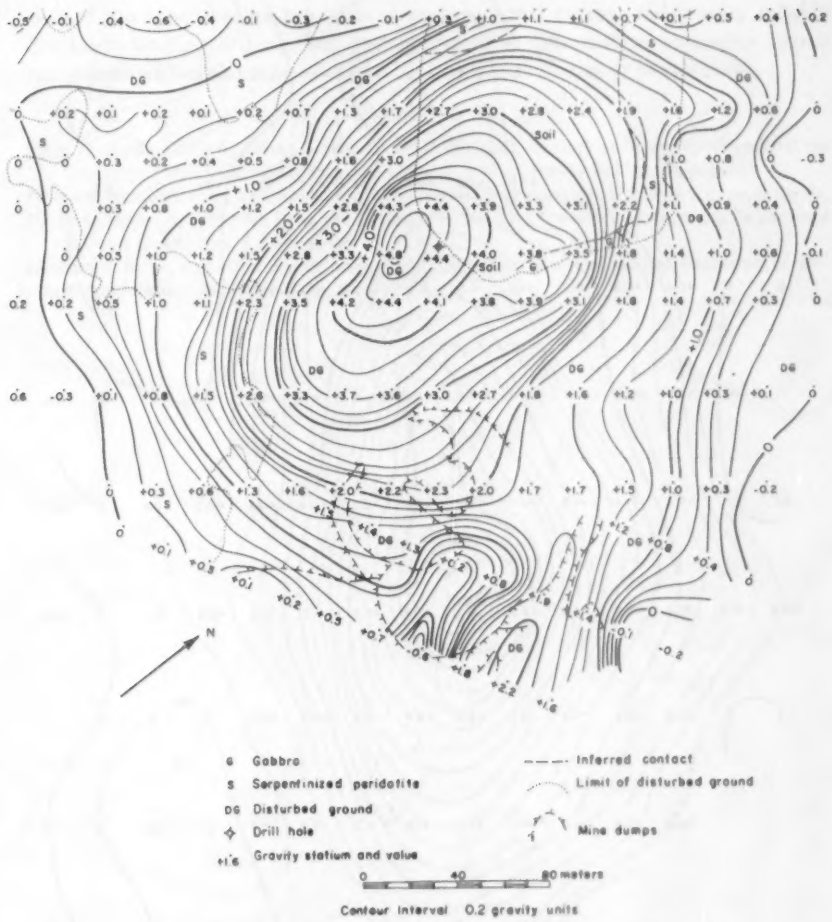

FIG. 13. Residual gravity anomaly caused by gabbro in serpentinized peridotite.

metric and geologic surveys in searching for chromite deposits in the Camaguey district. Because of the wide distribution of deposits, exploratory drilling undertaken without guidance resulting from preliminary geophysical and geological investigations would be economically unsound. The gravity measurements serve to delineate areas in which chromite may be found, and provide data for locating and determining depths of drill holes. Detailed geologic mapping provides essential information for evaluating and interpreting the gravity anomalies. Evalua-

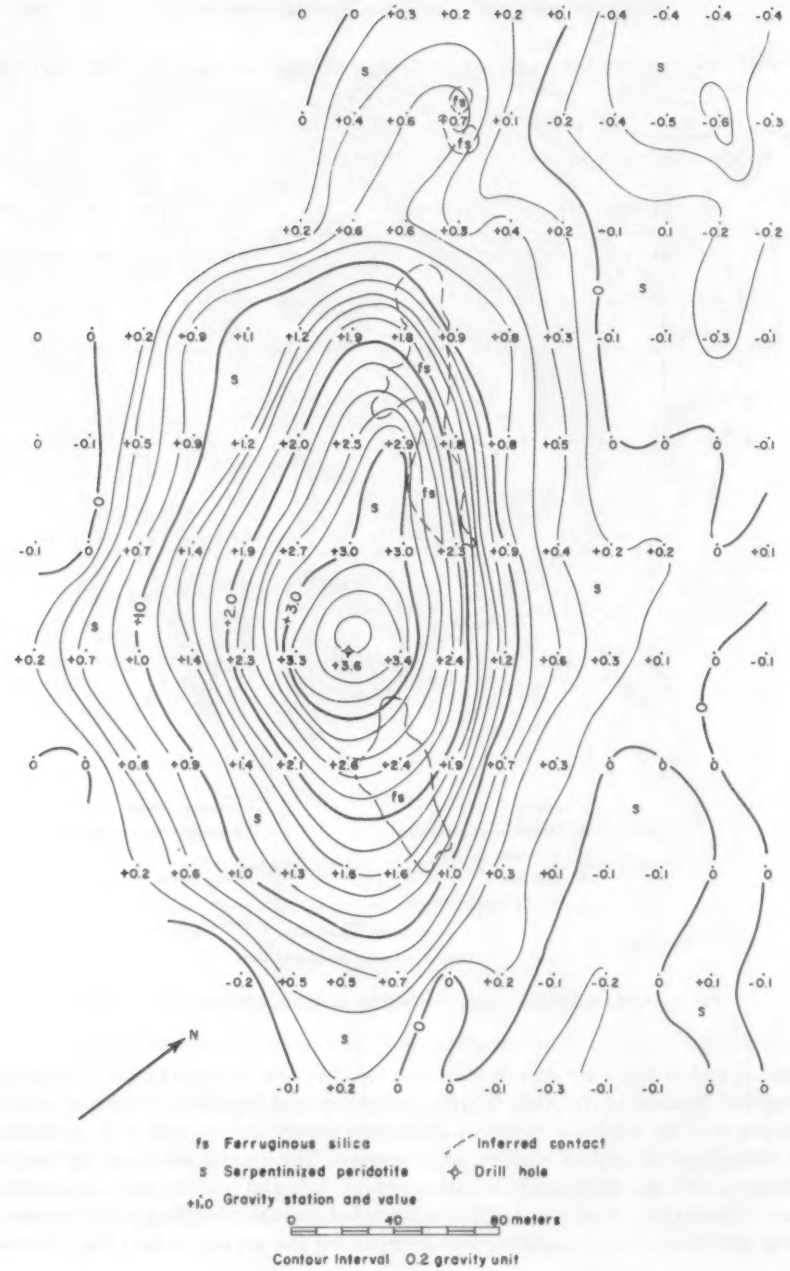

FIG. 14. Residual gravity anomaly over a body of rock composed essentially of magnesite, talc and quartz.

tion of the anomalies on the basis of geology, areal extent, and gravity relief is helpful in limiting drilling, but does not serve to differentiate anomalies caused by chromite from those associated with unexposed bodies of heavy rocks.

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GEOPHYSICS, VOL. XXII, NO. 4 (OCTOBER, 1957), PP. 870–886, 14 FIGS.

GEOPHYSICAL CASE HISTORY OF THE ANDERSON RANCH FIELD, LEA COUNTY, NEW MEXICO*

GLEN H. SWENUMSON†

ABSTRACT

The Northwest Shelf area of Southwest New Mexico has had an exceptionally rapid growth as an oil producing province. The Anderson Ranch field, discovered by the Continental Oil Company in 1953, is one of the typically prolific oil fields in this Northwest Shelf area. This field (Figure 1) is the most southwesterly of a series of Devonian oil fields in the Northwest Shelf area of New Mexico. It is located 22 miles west of Lovington, New Mexico in sections 2 and 11, T. 16 S.-R. 32 E., Lea County, New Mexico.

The Anderson Ranch area was first found to be anomalous by a shallow oil well drilled in 1927 which found the Rustler Anhydrite unusually high. Core drilling carried out in 1940 developed an Anhydrite nose over the area. A reflection seismograph survey was carried out in the period from 1950 to 1951 which succeeded in mapping a closed anticline in the face of many difficulties in obtaining usable seismograms. It is believed that the seismic map prepared for the deepest horizon was caused by multiple reflections. The anticline so revealed was drilled in a unitized drilling program and a well was completed in the Devonian for an initial potential of 1,968 barrels of oil per day. This was the discovery well.

EARLY EXPLORATION

The first indication of structure in the Anderson Ranch area was obtained by shallow subsurface geology. In 1927 the Caprock Oil and Gas Corporation drilled a well in section 11, T. 16 S.-R. 32 E. This well found the top of the Rustler Anhydrite (upper Permian) unusually high. No original maps exist but a search of old well data indicates that by 1938 the subsurface map drawn on the Rustler Anhydrite must have appeared somewhat as shown in Figure 2. For several years the nosing contours produced by the Anhydrite remained as a remainder of possible anomalous structure in the area. In 1940, Continental Oil Company began a core drill program to check Anhydrite structure in more detail over this nose. Rustler Anhydrite structure mapped by this core drilling is shown in Figure 3.

THE SEISMIC SURVEY

After accumulating some scattered leases over the general area of interest, the Continental Oil Company in December, 1950 began a reflection seismogram survey in an attempt to evaluate deep structure under the core drill anomaly. The party chief of the seismic crew at this time was Dale Fickinger who was later replaced by Ben W. Smith.

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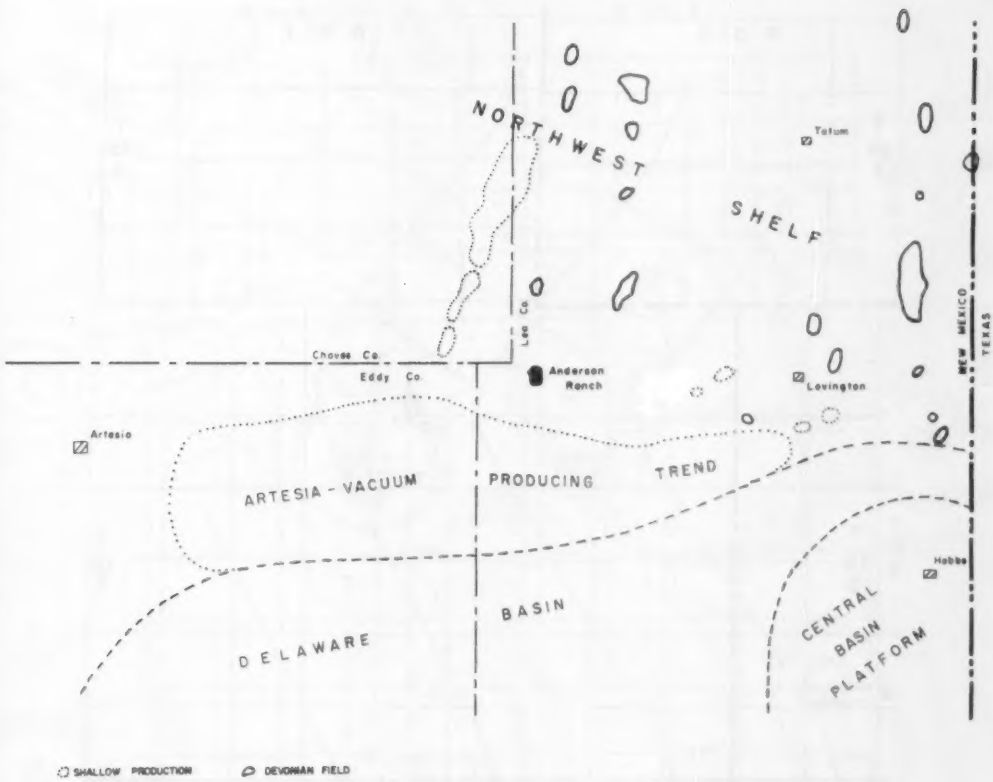

FIG. 1. Location plat of Anderson Ranch field, Lea County, New Mexico.

Many problems were encountered in the field operations. Seismograms were very poor. Deep shot holes were necessary and the holes could not be reloaded after the first shot because of a bed of unconsolidated sand which was betwen 200 and 300 feet thick. After numerous trials, a standard procedure was adopted using continuous profiles, six receptors per trace, split spreads, and a normal spread length of 1,320 feet. Twenty traces were recorded on each seismogram. Shotholes were bottomed in the Triassic redbed below the Ogallala sand at a depth of 330 feet.

Figure 4 shows typical seismograms obtained during the survey. Figure 5 shows some fair seismograms obtained during the survey. The quality of the seismograms was poor with practically no reflections recorded earlier than 1.0 second. Phasing, erratic and conflicting dips, and poor continuity were charac-

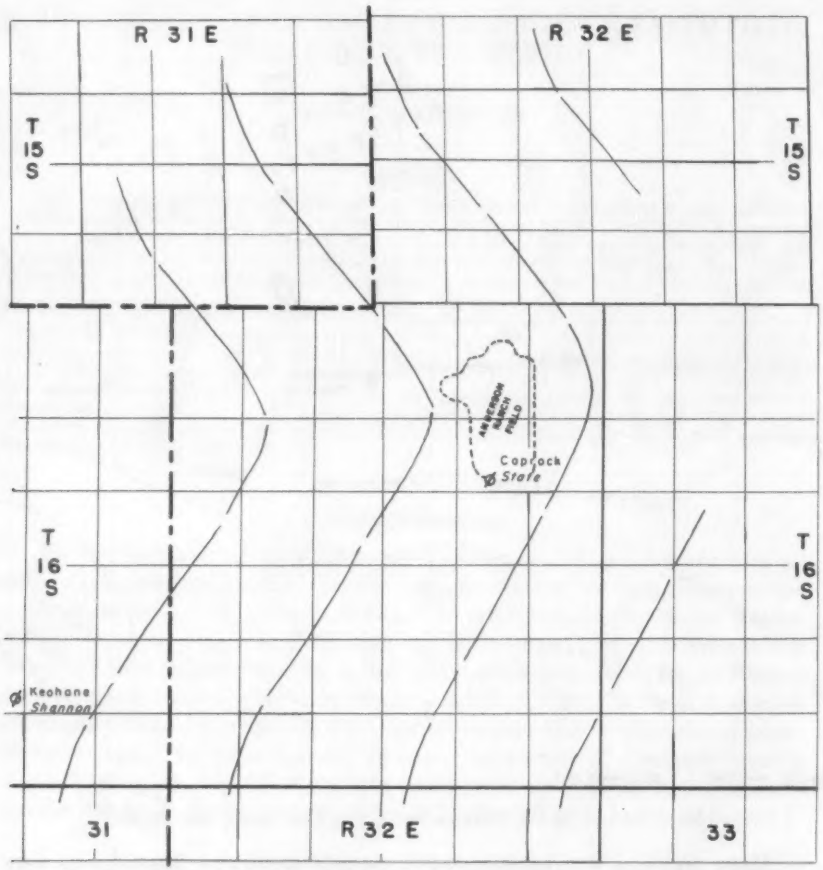

FIG. 2. 1938 regional subsurface map on top of Rustler Anhydrite. Contour interval is 100 feet.

teristic of the seismic records. The most consistent reflections were generally obtained between 1.5 and 2.0 seconds through the pre-Pennsylvanian section.

Figure 6 shows a West-East seismic time section across the Anderson Ranch structure. This line is about $2\frac{1}{4}$ miles long. It will be seen that the best seismic data lie in the range 1.5 to 2.0 seconds. The phasing and the numerous erratic dips shown on the section are typical of the area. Data are recorded on this section as late as 3.0 seconds. This can also be observed on the sample records shown in Figures 4 and 5.

Figure 7 shows a South-North time section across the structure. Part of this line (shotpoints 248–251) is covered by the sample records shown in Figure 4.

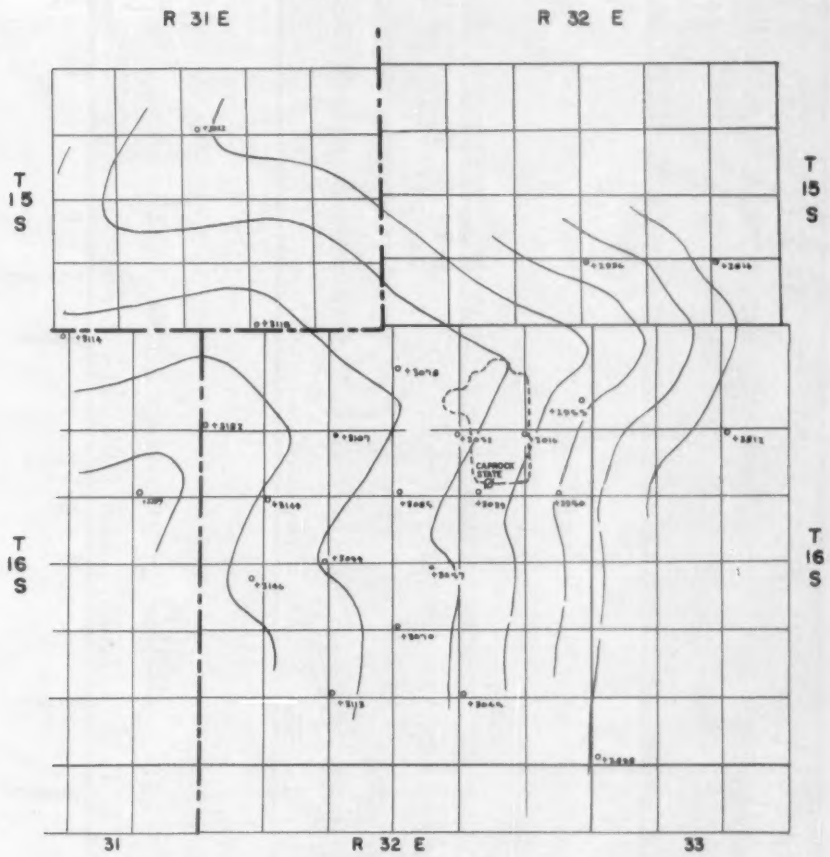

FIG. 3. Core drill map on top of Rustler Anhydrite. Contour interval is 50 feet.

The earliest reliable data again is for times greater than 1.5 seconds. Here again the unusually late events should be noted.

Events appearing as reflections were consistently recorded as late as 3.0 seconds. These events influenced the interpretation in the Anderson Ranch area. Because they did influence interpretation, some discussion of these late arrivals is given in the present paper.

The total thickness of section in the Anderson Ranch area is 17,000 feet as a best estimate. A velocity survey made in the Continental #2D Anderson Ranch well yielded an average velocity to the Devonian of 16,200 feet per second. It is believed that the reflection from the basement rock occurs at a reflection time of around 2.1 seconds. Some of the reflections occurring at times greater than 2.1

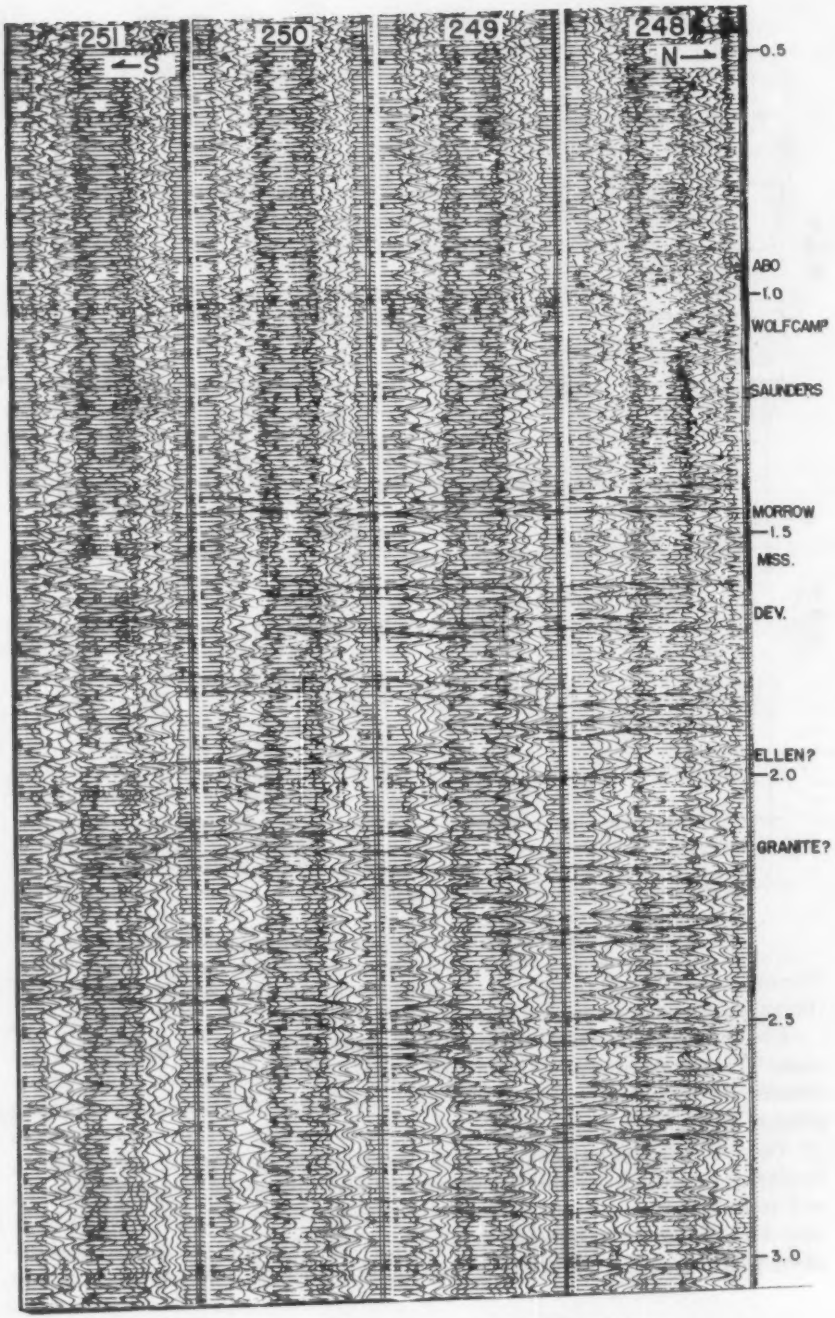

FIG. 4. Representative seismic records, Anderson Ranch area.

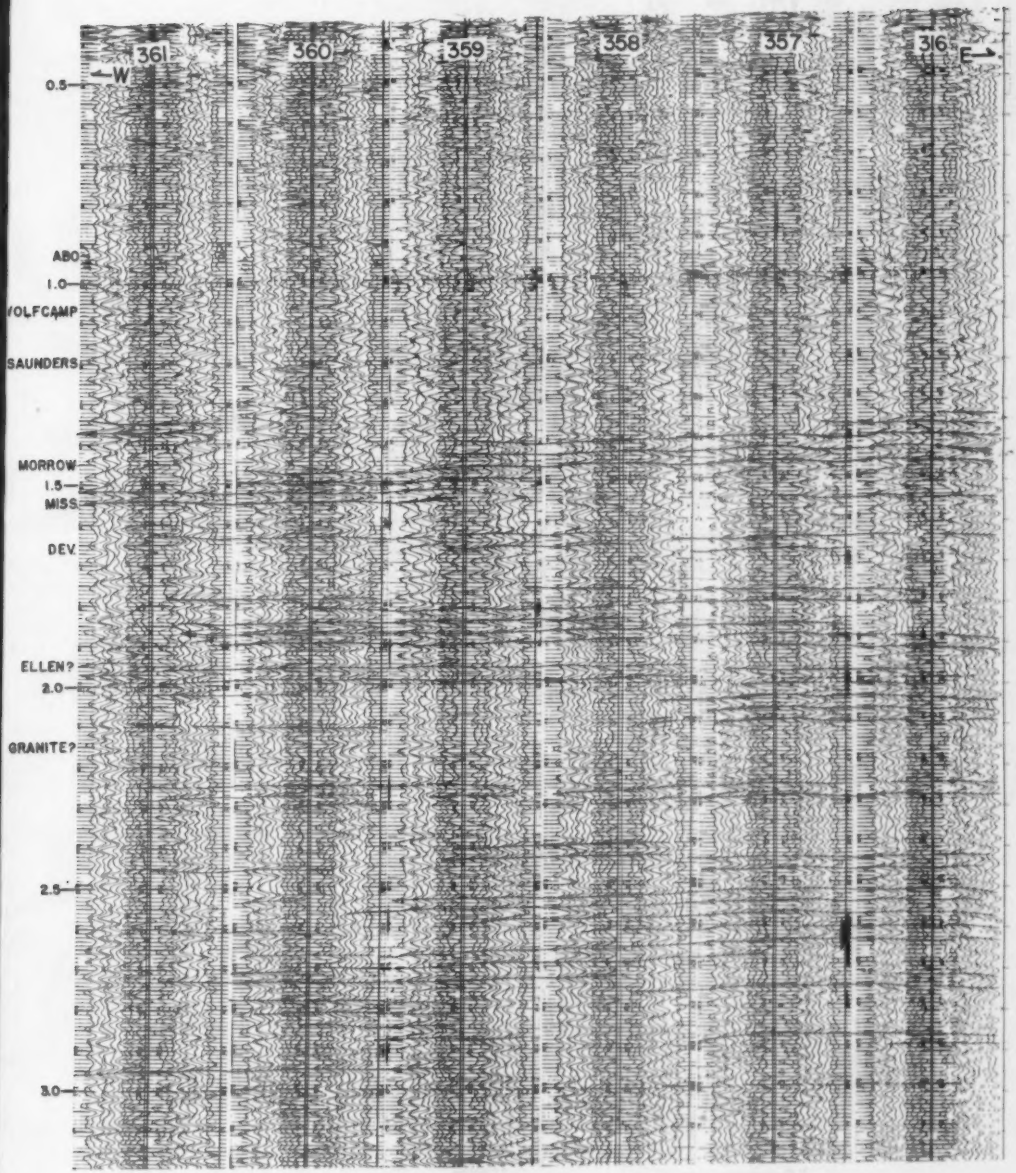

FIG. 5. Above-average seismic records, Anderson Ranch area.

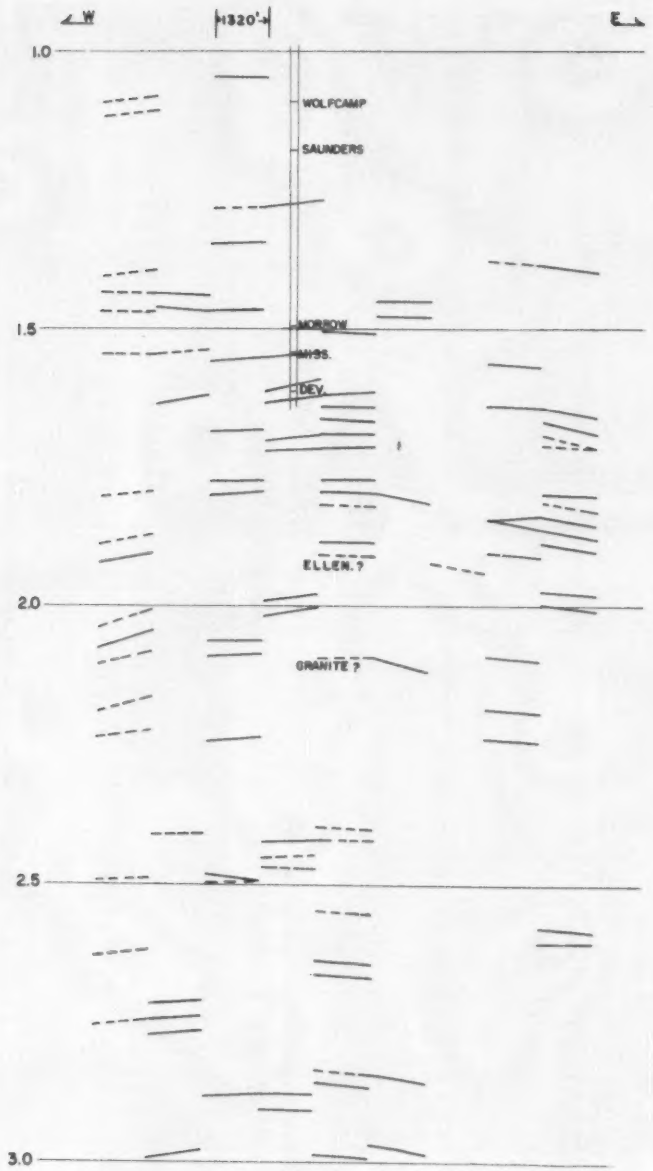

FIG. 6. West-East time section across Anderson Ranch structure.

FIG. 7. South-North time section across Anderson Ranch structure.

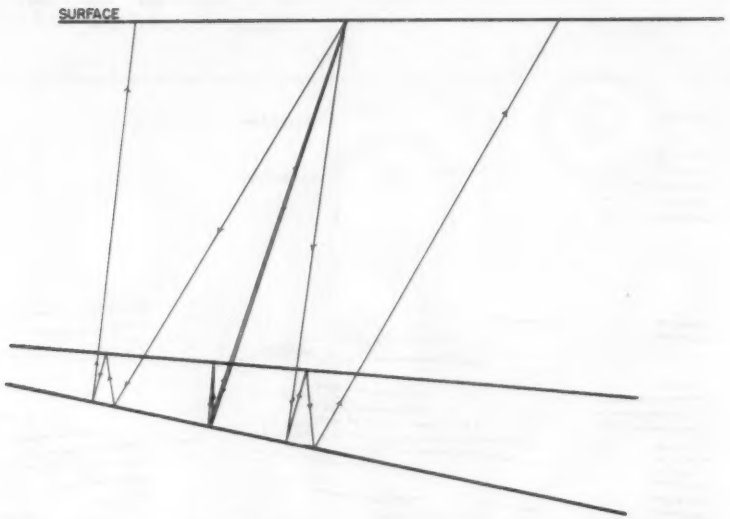

FIG. 8. Paths of multiple reflections between diverging beds. Sketch depicts a split spread setup.

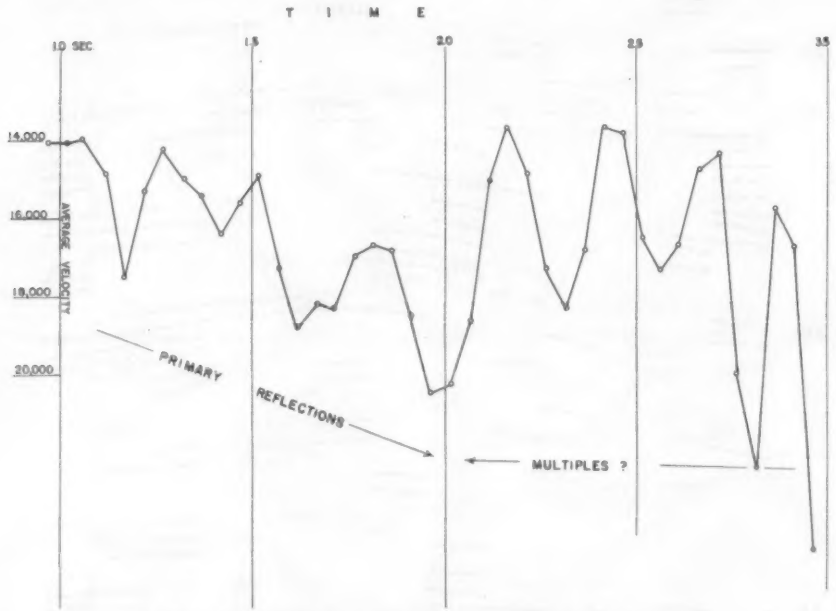

FIG. 9. Delta-T velocity determination, Anderson Ranch area.

seconds could have been caused by reflection interfaces within the basement rock, but it is believed that most of the events recorded in the range 2.1 to 3.0 seconds are multiple reflections.

If these events are truly multiple reflections, they were most likely caused by the strongly reflecting horizons in the 1.5 to 2.0 second region. It is possible that these apparent reflections could have been produced by multiples between the shallow horizons and the base of the low velocity layer. This is a favorite place for the occurrence of multiples. This, however, is believed not likely, since prominent primary reflections were not observed at shallow depths. This would indicate that low coefficients of reflection existed for the shallow horizons.

It will be observed that late events show dips which are generally in the same direction as, but somewhat greater than, dips from within the sedimentary section. The magnified dip shown by these alleged multiples suggests that these multiple reflections occur between diverging beds as has been sketched in Figure 8. In this case, both normal stepout and dip become exaggerated. That multiple reflections often show exaggerated dip has been observed by earlier authors of papers in GEOPHYSICS.[1]

Abnormally large stepout is considered an important criterion for recognizing an event as a multiple reflection. Near the close of the Anderson Ranch seismic survey, a statistical analysis of seismic velocities was prepared involving stepout readings from 397 spreads. The curve shown in Figure 9 is quite ragged, but it will be observed that this analysis showed the normal increase in velocity with depth down to an arrival time of about 2.0 seconds. Between 2.0 and 2.8 seconds, the computed velocities decreased, indicating that abnormaly large stepout did predominate late on the records. To recapitulate, multiple reflections appear to explain the persistent late events.

The maps shown in Figures 10, 11, and 12 are drawn from the original data as they appeared before drilling. The most reliable and consistent zones on the seismic records were chosen for the preparation of these seismic structure maps. Two continuous correlation maps were prepared. The shallowest map designated by "upper zone" and shown in Figure 10 was drawn for a reflection time of 1.8 seconds. This later proved actually to represent the lower Devonian. The map designated by "pre-Pennsylvanian" and shown in Figure 11 with a reflection time of 2.07 seconds probably represents basal Ellenburger limestone.

Figure 12 shows a dip map prepared from dips in the zone between 2.4 and 3.0 seconds. By converting this time zone to feet, it would appear that this zone spans a depth range of 19,600 to 24,600 feet and so lies from 2,600 to 7,600 feet below the estimated top of the granite. This map designated by "lower dip" is probably drawn from multiple reflection data. At the time the shooting was being carried out, this map was, in fact, annotated "possible multiple reflections." It must be kept in mind that this shooting was done in 1950 and that no pre-Permian holes had been drilled within the survey area, so the survey was not tied to any

[1] See articles by T. P. Ellsworth, C. H. Johnson, and J. C. Waterman, v. 13, 1948.

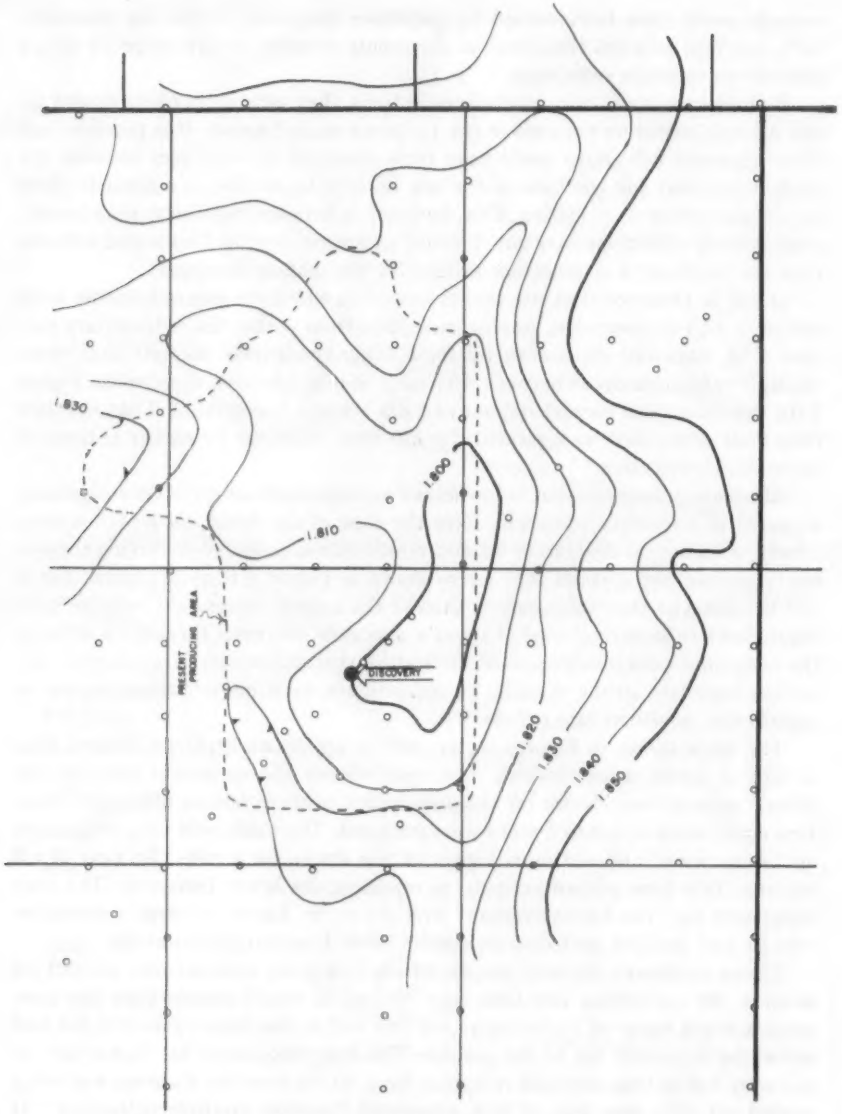

FIG. 10. Reflection seismic map of "upper zone." Subsequent drilling showed this map to represent a "lower-Devonian" horizon. Contour interval is .010 second.

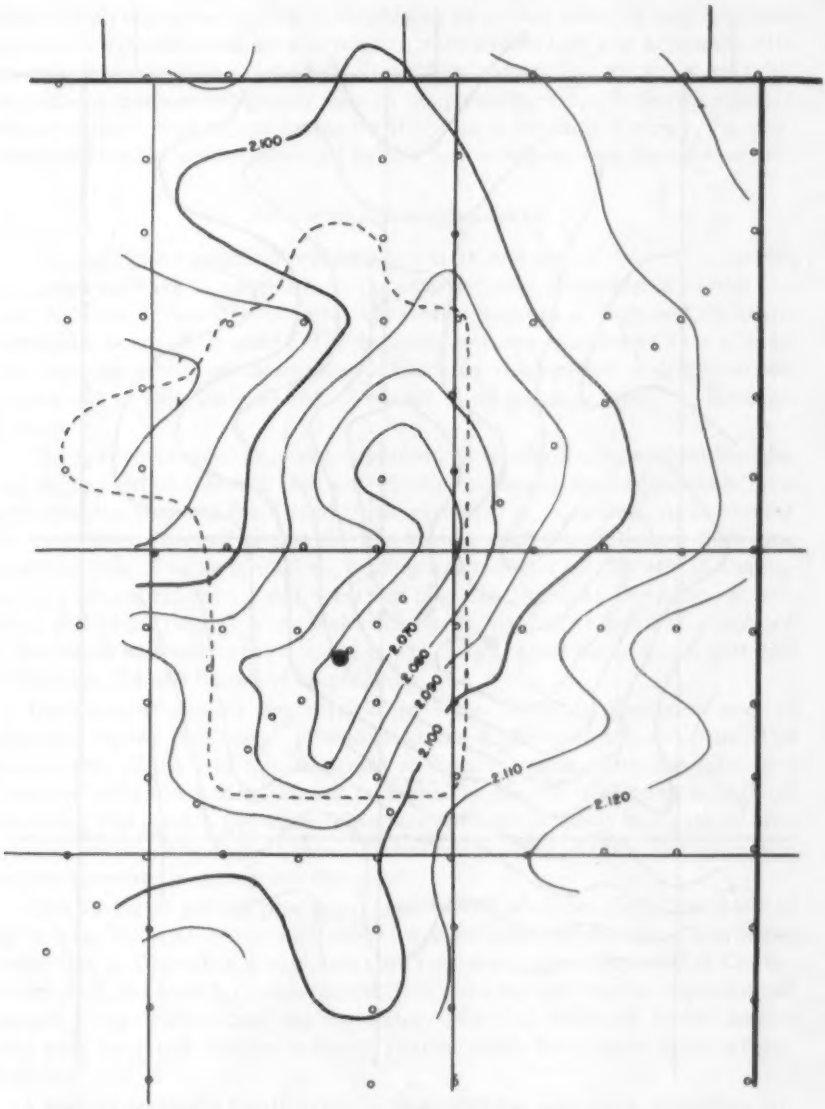

FIG. 11. Reflection seismic map of "pre-Pennsylvanian." This map probably represents a horizon near the base of the Ellenburger. Contour interval is .010 second.

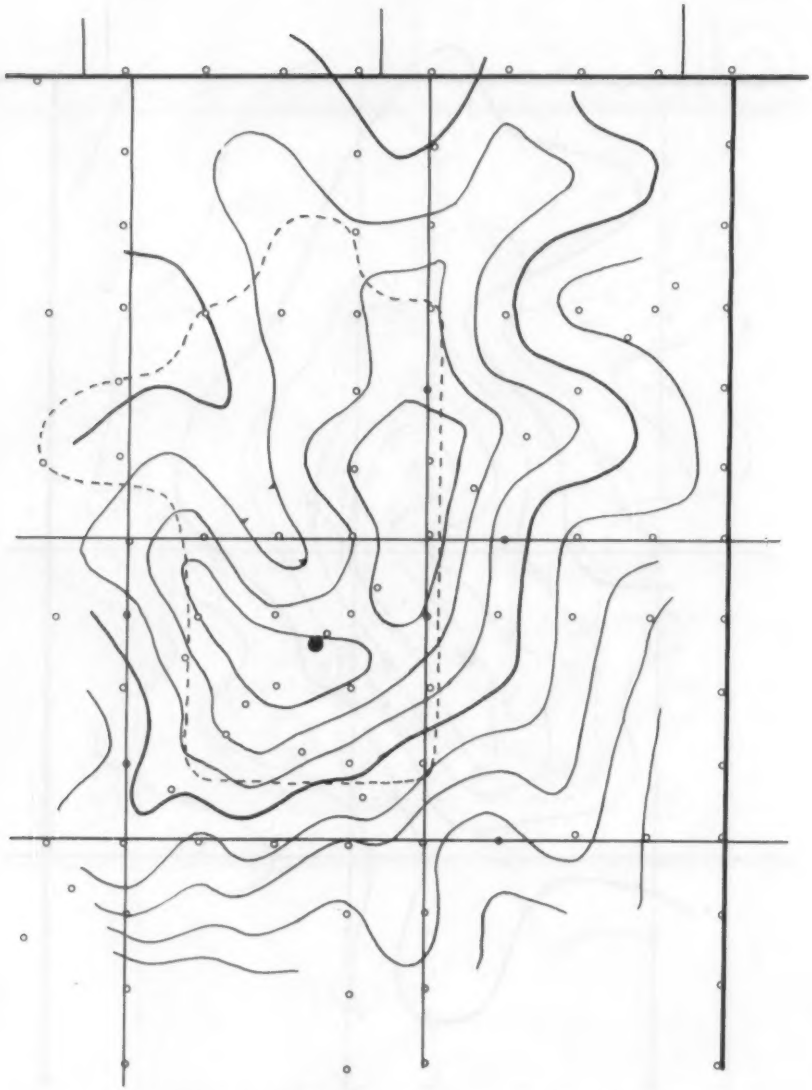

FIG. 12. Seismic dip map from the "lower dip" zone (2.4 to 3.0 seconds interval). This map is probably based on multiple reflection "dips." Contour interval is .010 second.

deep hole stratigraphic marker. It should also be noticed that this map is in close agreement with the continuous correlation maps and, in fact, is in agreement with present producing limits of the field. It will be observed that the structural relief on this map is somewhat greater than on the preceding maps. Referring again to the north-south time section across the structure as shown in Figure 7, the magnified relief in the zone represented by this map is apparent on the time section.

DISCOVERY AND DEVELOPMENT

Although many technical problems had to be met during the seismic survey, the closed anticline as mapped from the seismic data was considered worthy of a test. A "State of New Mexico" unit was formed from the acreage over the structure and a location was staked. The discovery well was spudded on June 9, 1952. The first commercial oil shows were encountered at 9,750 feet. A drill stem test carried out at this depth flowed 28 barrels of oil per hour from the Saunders formation.

The next commercial oil shows appeared in a spectacular manner on September 20, 1952 when this well blew out while preparations were being made for a drill stem test from the Bend Sand (Pennsylvanian) at 12,142 feet. After blowing for three days, the well caught fire and burned until September 27. Following extensive hole cleaning operations, drilling was resumed on this well in December. On March 11, 1953, a drill stem test from the Devonian flowed 409 barrels of 54 gravity oil through a one inch choke in 11 hours. The well was completed in Devonian dolomite in the interval 13,374 to 13,474 feet for an initial potential production of 1,968 barrels of oil per day.

Development drilling has resulted in eight Devonian producers and 14 Saunders "lower Wolfcamp" producers on the Anderson ranch structure. The greater part of the field was developed on 80 acre spacing with Devonian and Saunders wells alternating. Figure 13 shows the present Wolfcamp subsurface structure. The present Devonian subsurface structure is shown in Figure 14. The contour interval is 20 feet. It should be noticed that the verified Devonian subsurface structure is of only 100 feet relief.

This field is at present producing 3,600 barrels of oil per day. Two-thirds of the production is Devonian and one-third is Saunders production. Cumulative production to December 1, 1956, less than four years after completion of the discovery well, has been 3,327,000 barrels. It is quite evident that an important oil discovery has resulted from the exploratory efforts at Anderson Ranch despite very poor data and despite technical puzzles which have never been entirely resolved.

I wish to thank the Continental Oil Company for permission to publish this paper and I wish also to thank my many associates in the Continental Oil Company for advice and for historical information.

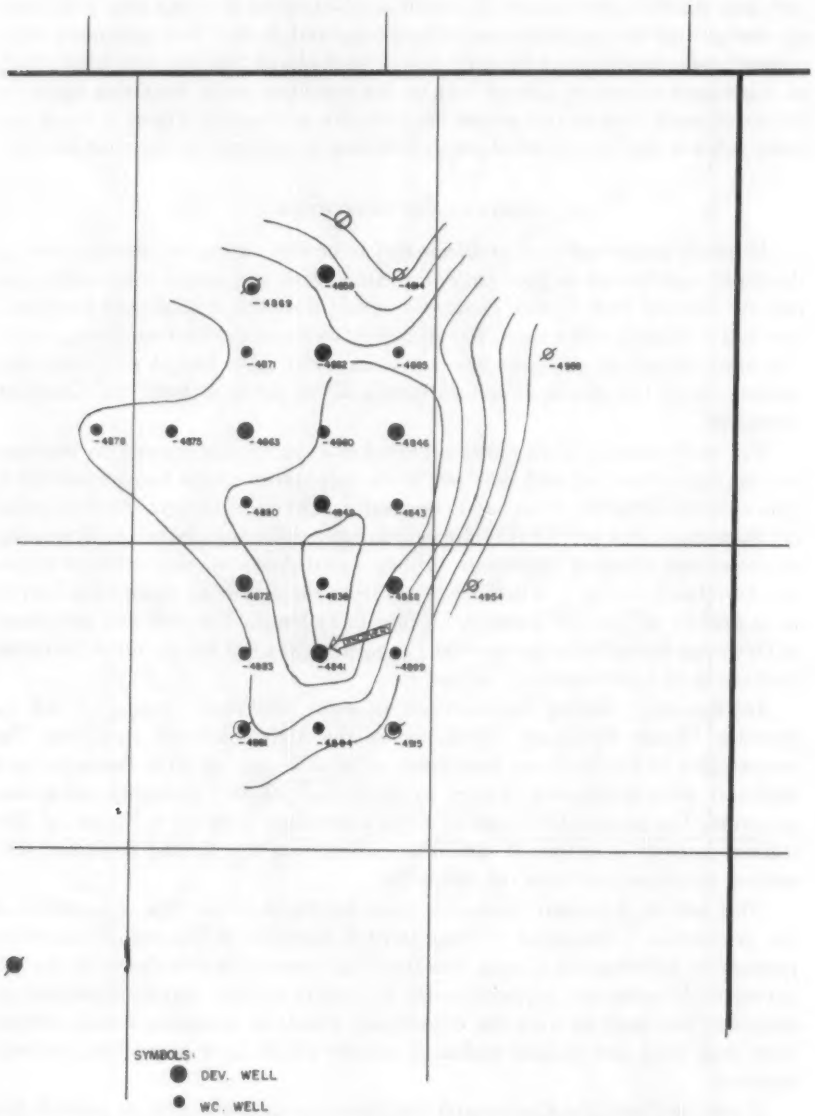

FIG. 13. Subsurface structure map on the Wolfcamp (electric log marker). Contour interval is 20 feet.

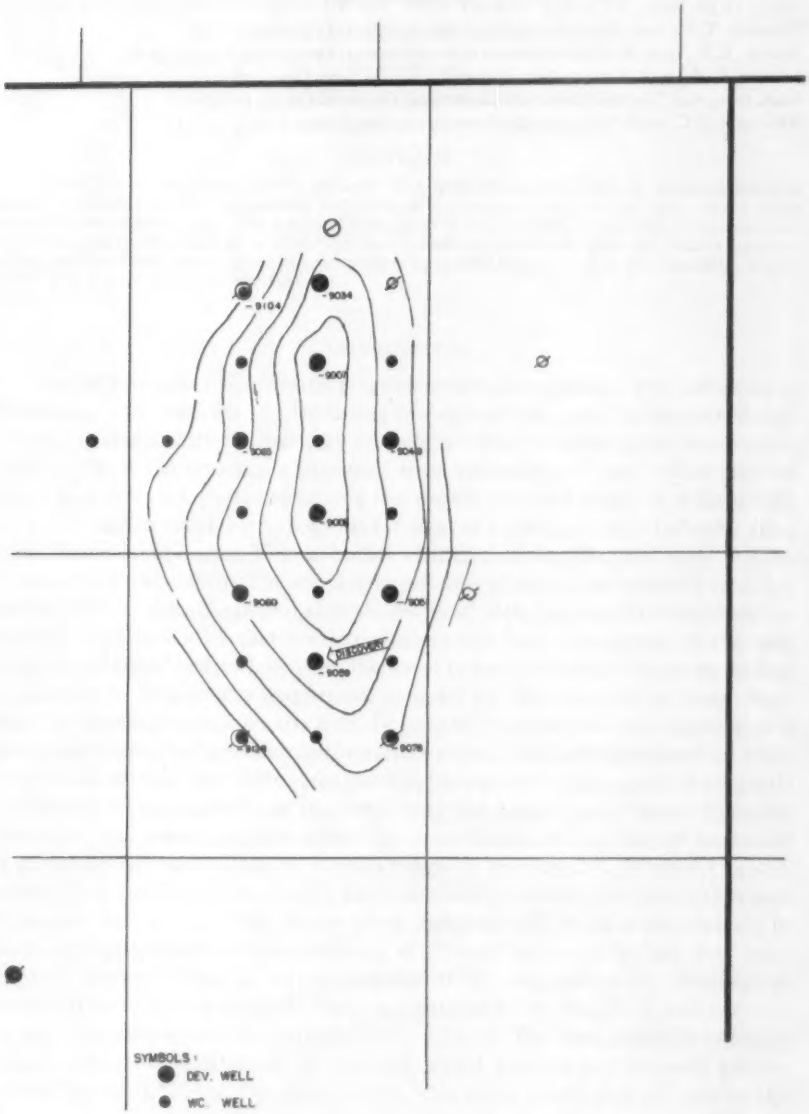

FIG. 14. Subsurface map on the top of the Devonian. Contour interval is 20 feet.

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GEOPHYSICS, VOL. XXII, NO. 4 (OCTOBER, 1957), PP. 887–904, 10 FIGS.

GRAPHICAL CALCULATION OF TOTAL-INTENSITY ANOMALIES OF THREE-DIMENSIONAL BODIES*

ROLAND G. HENDERSON† AND ISIDORE ZIETZ†

ABSTRACT

Calculation of the total-intensity anomaly of a three-dimensional body of arbitrary shape is greatly facilitated by the orthographic projection of a topographic map of the body onto a plane normal to the inducing field. The graphical integration is then effected by a modified Gassmann integration process. Applications to theoretical and laboratory models establish the relative accuracy of the method. Examples are given of applications to observed anomalies over two laccoliths, Round Butte and Square Butte, in Montana.

INTRODUCTION

The high accuracy of airborne magnetometer data together with advances in knowledge and methods of accounting for regional magnetic anomalies should permit excursions into the virtually unexploited field of determining structure or topography in the crystalline basement from aeromagnetic data. Often one can make an intelligent guess concerning the depth, size, and shape of a disturbing body but cannot check his hypothesis for want of a general method of computing three-dimensional bodies, that is, bodies with three dimensions not large in comparison with the depth. The application of two-dimensional methods (see Appendix III) to three-dimensional problems is of little help as these methods invariably lead to bodies that are too small or too deep. The sphere is the only three-dimensional body whose complete total-intensity anomaly is computable in a closed form. The axially magnetized cylinder can be computed in closed form only for anomaly points on the axis. In general, to interpret the anomaly of a body magnetized by induction in the earth's normal field, recourse must be made to approximations. Very little attention has been given to this aspect of magnetic interpretation, largely because the complexity has been overestimated. Vacquier (Vacquier, and others, 1951) suggests the computation of an album of anomalies of model horizontal laminae in various magnetic inclinations. In model experiments, Zietz and Henderson (1956) have obtained the fields of horizontal laminae in various inclinations. This album when complete will be an invaluable aid in obtaining approximations to anomalies of three-dimensional bodies. For more accurate determinations in any inclination of the magnetic field, graphical or numerical methods are required. Such calculations for vertical (ΔZ) and horizontal (ΔH) intensity anomalies are admittedly difficult. The total-intensity anomaly being a linear combination of ΔZ and ΔH would seem to involve even greater computational difficulty. On the contrary, this paper shows that ΔT can be the

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most easily computed anomaly for three dimensional bodies; and that a general, accurate, and practical process that does not involve a prohibitive amount of effort is possible.

BASIC ASSUMPTIONS

In airborne magnetometry the quantity measured is ΔT, the component of the total-magnetic-intensity anomaly in the direction of the total field vector. Because this direction is not known from the measurements, the direction of the earth's normal field (assumed to be uniform over the area) is adopted as the direction of ΔT. It has been shown by Hughes and Pondrom (1947) that this approximation results in a negligible error for the anomalies commonly observed in exploration work. As far as susceptibility is concerned the bodies to be dealt with are assumed to be homogeneous, isotropic, and uniformly polarized. Furthermore, any remanent magnetization is assumed to be codirectional with the normal field; otherwise the body is magnetized entirely by induction. These assumptions are an over-simplification of a complex situation; nevertheless experience has established that they are reasonable. Many cases are reported in the literature showing that these assumptions have led to results that were substantiated by independent geologic and geophysical evidence.

TRANSFORMATION OF COORDINATES

Consider a body of irregular shape magnetized by induction in a normal field of strength T_0 and inclination I as shown in Figure 1. Suppose the problem is to calculate the magnetic anomaly at P, due to the body indicated. Conventionally, a right-handed coordinate system is taken with origin at P, the x-axis positive towards magnetic north and the z-axis positive vertically downward. Each volume element $dxdydz$ will have vertical and horizontal components of magnetization of strength kZ_0 and kH_0, where k is the magnetic susceptibility, assumed to be uniform throughout the body. The anomaly at P would be obtained by summing the effects of these volume elements over the entire body. The mathematical mormulation is the following:

$$\Delta Z = kZ_0 \iiint [(3z^2 - r^2)/r^5]dxdydz + kH_0 \iiint (3xz/r^5)dxdydz \quad (1)$$

$$\Delta H = kH_0 \iiint [(3x^2 - r^2)/r^5]dxdydz + kZ_0 \iiint (3xz/r^5)dxdydz \quad (2)$$

$$\Delta T = \Delta H \cos I + \Delta Z \sin I \quad (3)$$

For an arbitrary geometry the evaluation of these integrals would be formidable, with two volume integrations each for ΔZ and ΔH or three volume integrations for ΔT. This is an excessive amount of work for a value at just one point. Fortunately the difficulty is not inherent and can be reduced to a minimum merely by a change in point of view.

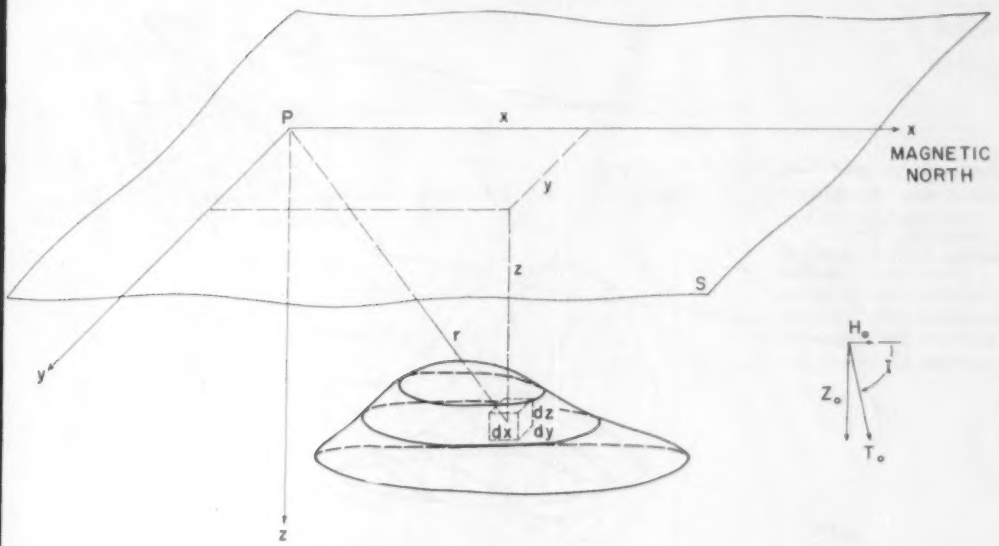


FIG. 1. Body and usual coordinate system.

Instead of a horizontal reference plane consider an inclined reference plane S' perpendicular to the direction of T_0, as in Figure 2. This amounts to rotating the coordinate system about the y-axis so that the z-axis, now designated z', is in the direction of the normal field. In the primed coordinate system $Z_0' \equiv T_0$, H_0' vanishes because T_0 can have no components at right angles to itself, and $I' = 90°$. The formula for ΔT simplifies then to

$$\Delta Z' = \Delta T = kT_0 \iiint [(3z'^2 - r^2)/r^5] dx dy dz \qquad (4)$$

This interesting result implies that by a simple rotation of the coordinates of the body, an aeromagnetic anomaly can be computed with a third of the conventional effort for ΔT and half the conventional effort for ΔZ or ΔH. It is more desirable to transform the coordinates of the body than to transform the field as suggested by Hughes and Pondrom (1947) and Baranov (1955). The coordinate transformation involves only an elementary projection. Initially the body is represented by a contour map on plane S. The immediate problem is to obtain contours of the body on the inclined plane S'. If the body is cut by a series of equally spaced planes parallel to the inclined plane, the distances of the resulting sections from S' establish the required contours on the S-plane. The process is best explained by an actual problem.

Figure 3 is a topographic map of Round Butte, a laccolith in the Highwood

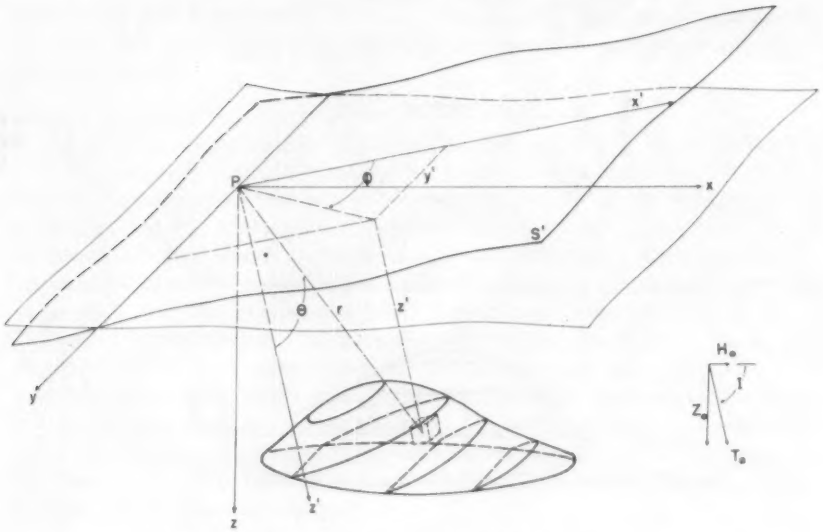


FIG. 2. Coordinate system rotated about y-axis with z'-axis codirectional with T_0.

Mountains area, Montana. The mass above the 4,600-foot contour will be used to demonstrate the transformation. The magnetic inclination is 73°, the declination is 19°. Conventional x- and y-axes are established with the origin somewhere near the center of the mass. In the new coordinate system y is invariant, and the x'-axis makes an angle of 17° with the x-axis. Vertical sections parallel to the x-axis are taken at a representative number of points along y. A typical vertical section A–A' is shown in the insert. A series of lines is drawn parallel to S' and intersecting the body. The projection of these intersections onto S' together with their depths below S' establish the contour through them. These data, when plotted and contoured, give the orthographic projection of the body shown in Figure 4.

Broken lines indicate the continuation of the contours on the underside of the body. The projection preserves east-west dimensions and foreshortens north-south dimensions. The process applies at all magnetic latitudes. The body can now be calculated from (4) above. The Round Butte body will be discussed further after a digression on the graphical evaluation of the integral in question.

Many authors, Pirson, Roman, Gassmann, Baranov to mention a few, have developed graphical methods for calculating three-dimensional magnetic bodies. The essential difference among them rests either in the kind of coordinate system used or in the order in which the integration proceeds in respect to the several variables. Gassmann (1951) presents an ingenious yet highly effective method.

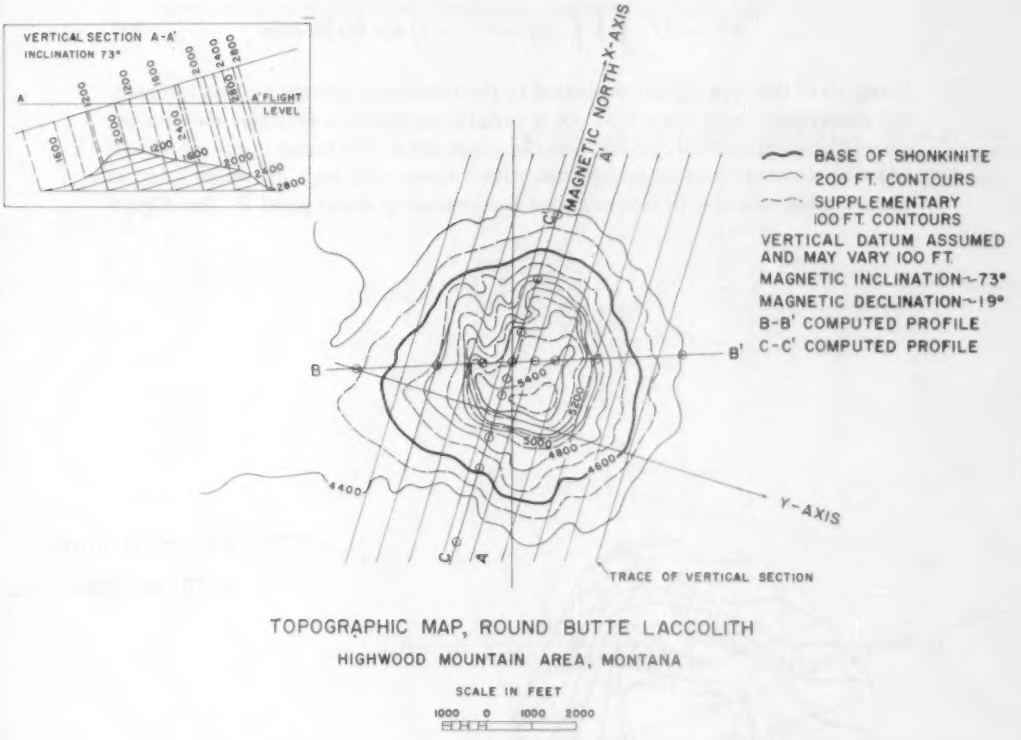


FIG. 3. Topographic map, Round Butte Laccolith.

His discussion is essentially for gravity data, but the extension to magnetic data is simple and straightforward.

For details of the Gassmann integration process, Gassmann's paper should be consulted. For the sake of completeness, the process is summarized as follows:

Consider the body shown in the upper left corner of Figure 5 as having a simple attitude in relation to the prime coordinate axes. The contours of the body are shown at lower right in the figure. Use will be made of spherical polar coordinates related to rectangular coordinates by the following transformation.

$$x' = r \sin\theta \cos\phi$$

$$y' = r \sin\theta \sin\phi$$

$$z' = r \cos\theta$$

The integral (4) becomes then

$$\Delta T = kT_0 \iiint [(3\cos^2\theta - 1)\sin\theta/r]drd\theta d\phi \qquad (5)$$

Integrals of the type (5) are evaluated in the Gassmann process by first integrating numerically with respect to the ϕ variable to obtain a fictitious two-dimensional "concentrate" of the body on the plane $\phi=0$. We found it convenient to use a 64-element circle in conjunction with a linear rule, each drawn on a transparent medium and each free to rotate independently about point P. (See Figure

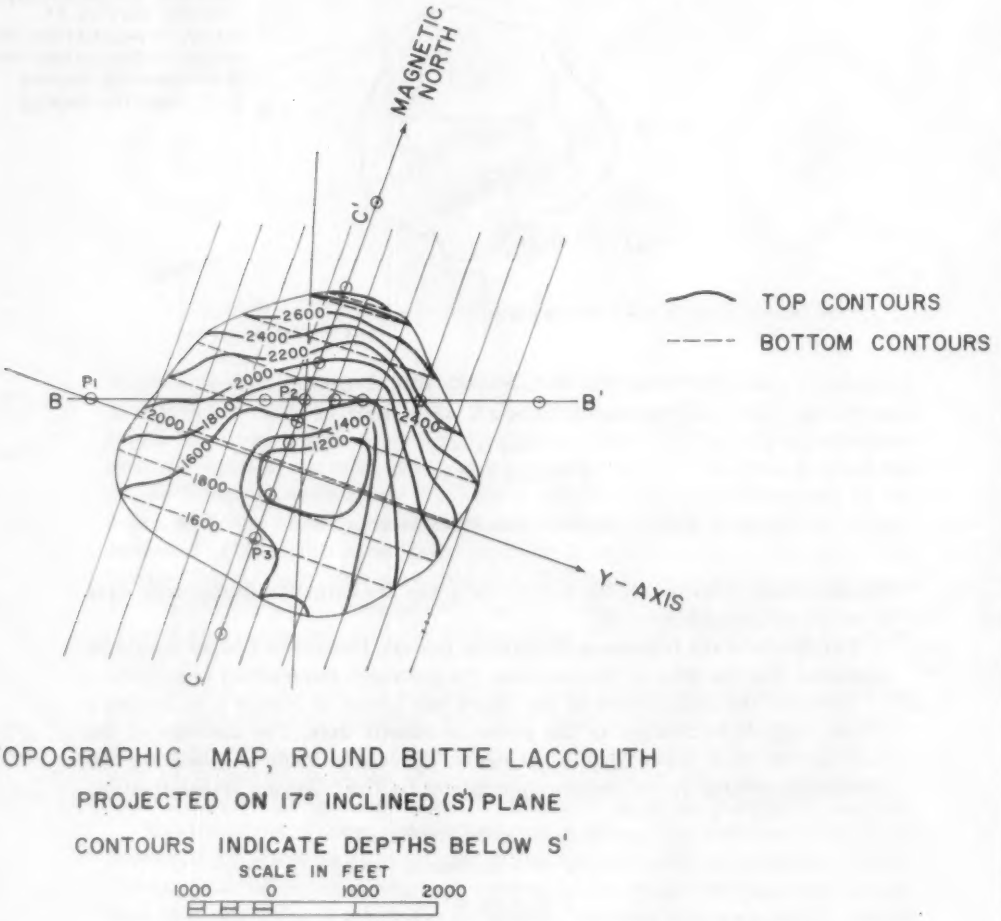


FIG. 4. Topographic map, Round Butte Laccolith projected on inclined plane.

GASSMANN INTEGRATION PROCESS – MAGNETIC APPLICATION

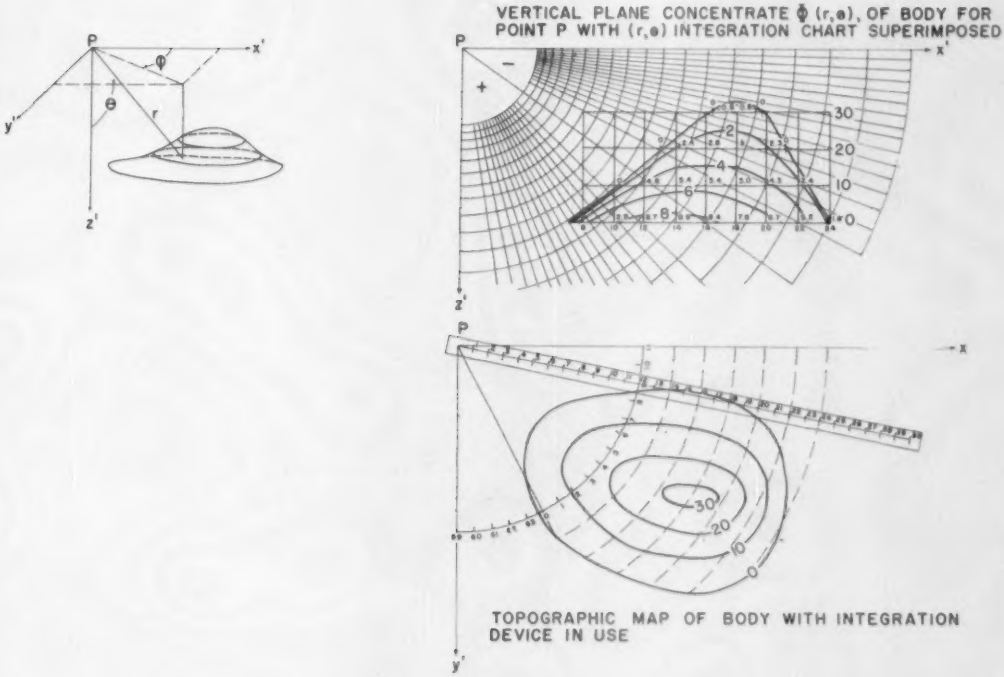


FIG. 5. Gassmann integration process, magnetic application.

5, lower right.) With this device arc lengths for each level are measured at various radial distances on the rule, and the values recorded at the proper level in the $\phi = 0$ plane shown at upper right in Figure 5. These values are contoured as the concentrate, $\Phi(r, \theta)$. Actually $\Phi(r, \theta)$ represents the length of arc cut from a given contour level by a cone of slant height r and angle θ. The volume integral in (5) is thus reduced to the surface integral

$$\Delta T = (\pi k T_0/32) \iint [\Phi(r, \theta)(3 \cos^2 \theta - 1) \sin \theta / r] dr d\theta \qquad (6)$$

The surface integration is accomplished with the aid of a (r, θ) graticule, which varies radially as $\log r$ and angularly as the function $\sin^2 \theta \cos \theta$. The graticule,

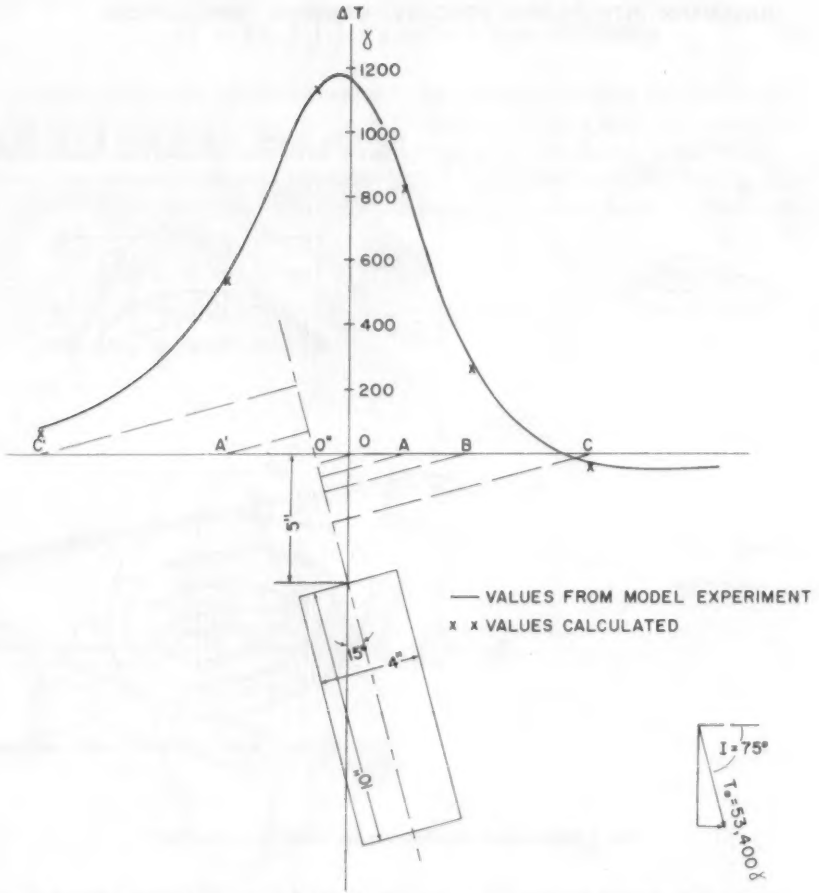


FIG. 6. Observed and computed total-intensity anomaly of inclined cylinder.

one-half of which is shown upper right in Figure 5, was constructed so that each compartment has the effect of 0.117 $\bar{\Phi}_{ij}(r, \theta)$ gammas at point P, for an inducing field of 50,000 γ and a susceptibility of 0.01 cgs units, where $\bar{\Phi}_{ij}(r, \theta)$ is the average value of $\Phi(r, \theta)$ over the (ij)th compartment. The values $\bar{\Phi}_{ij}(r, \theta)$ summed over the concentrate and adjusted for susceptibility and inducing field give the required anomaly at P.

APPLICATIONS TO THEORETICAL BODIES

The method was tested on theoretical anomalies of spheres and vertical cylinders and yielded errors of about 1 percent. The results of a test involving the

transformation of the coordinates of a body are shown in Figure 6. The body is a 4-inch diameter right circular cylinder 10 inches long. The cylinder is parallel to an inducing field of strength 53,400 γ and inclination 75°. A model of this cylinder composed of a mixture of one part magnetite and two parts gypsum plaster by volume was measured in the authors' magnetic model experiments at the Naval Ordnance Laboratory. The solid curve represents experimental data. Values calculated by transformation and Gassmann graphical integration are indicated by x's. The contours of the concentrates, not shown, are simply a series of parallel lines bounded by a rectangle 10 inches high for each point. The apparent volume susceptibility as determined in the experiment is 0.059 cgs. These results indicate that the method is accurate and can be used to compute the theoretical anomaly of any geometry representable in the form of a contour map. Within the limitations imposed by the fundamental assumptions, the method is applicable to geologic problems when there is sufficient control.

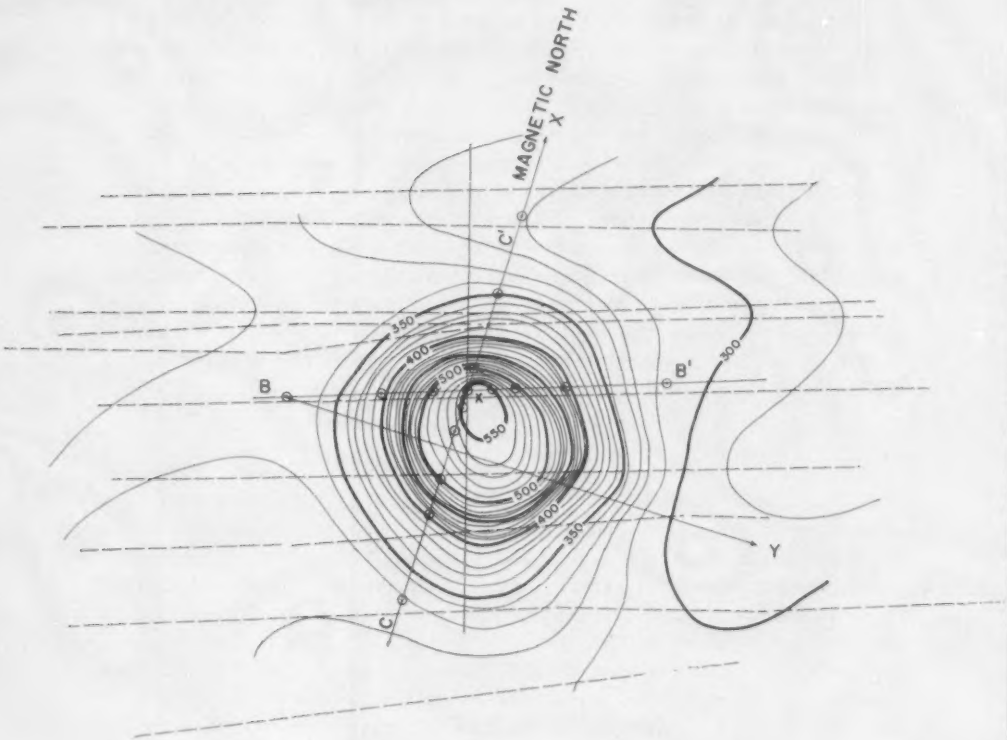
GEOLOGIC APPLICATION

Round Butte laccolith, a prominent topographic feature in the Highwood Mountain area of Montana, already mentioned, lends itself as a likely body for a practical application of the method. The igneous mass was intruded into the Eagle sandstone of Late Cretaceous age. The sedimentary cover has been completely eroded leaving dark granitic-textured shonkinite, capped by a lighter, more feldspathic syenite. The geology has been discussed by Pirsson (1905), Hurlbut (1939) and others.

The bottom contact between the lower shonkinite and Cretaceous sandstones is not exposed. It is proposed in this paper, therefore, to calculate the anomaly of the exposed mass by the method outlined above, and to compare it with the observed anomaly in the hope that the misfit might permit speculations on the depth extent of the unexposed portions.

The size and the shape of the exposed mass were obtained from the contour map (Fig. 3) prepared for the purpose by the Geological Survey. The susceptibility, as determined from measurements on 10 samples in the U. S. Geological Survey laboratory was on the average $(4.3 \pm 0.6) \times 10^{-3}$ cgs units. The syenite and shonkinite had about the same susceptibility; there was little variation in susceptibility from sample to sample. The entire mass may therefore be regarded as essentially homogeneous as far as induction theory is concerned.

Round Butte was flown at 6,500 feet above mean sea level, with east-west flight lines at approximately $\frac{1}{4}$-mile spacing. The striking resemblance between the topographic (Fig. 3) and aeromagnetic (Fig. 7) maps suggests that the topography plays a major role in producing the anomaly. From Weed and Pirsson's geologic map, Pirsson (1905), the generalized sandstone-shonkinite contact may be taken at the 4,600 foot-contour. Profiles B-B' and C-C' were computed at the encircled points. It has already been shown how this body is transformed by an orthographic projection to simplify calculations. The transformed body together with typical Gassmann type concentrates for points P_1, P_2 and P_3 are re-



TOTAL-INTENSITY AEROMAGNETIC MAP, ROUND BUTTE, MONTANA

RELATIVE TO ARBITRARY DATUM
CONTOUR INTERVAL, 10 GAMMAS
FLOWN APPROXIMATELY 6500 FT. ABOVE SEA LEVEL

SCALE IN FEET
1000 0 1000 2000

FIG. 7. Total-intensity aeromagnetic map, Round Butte, Montana.

viewed in Figure 8. Similar concentrates were obtained for all the points to be computed. The diagram at lower left in this figure shows how the x_0' and z_0' coordinates of the points P_1, P_2 and P_3 are determined graphically. As an alternate approach, $x_0' = x \sin I$, $z_0' = x \cos I$. The locations of P_i on the z' axis are shown at the right. The (r, θ) integration chart was used on each concentrate in turn.

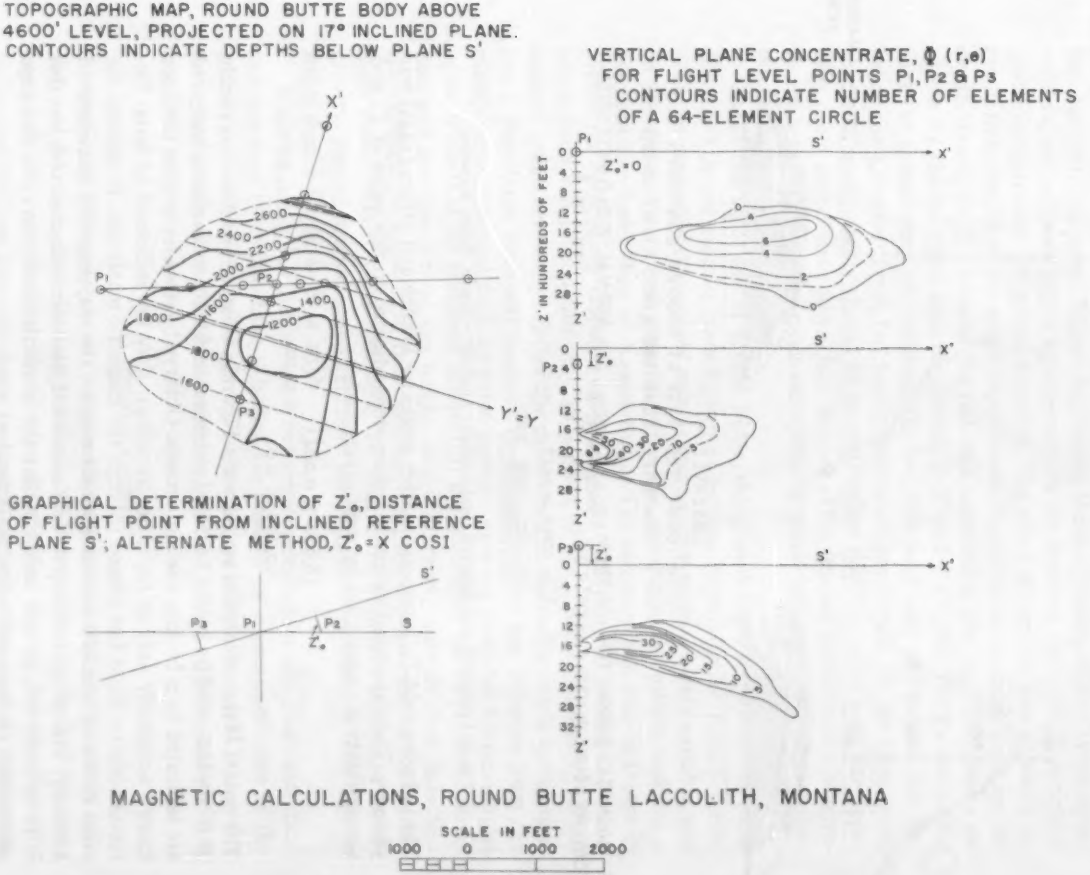


FIG. 8. Magnetic calculations, Round Butte Laccolith, Montana.

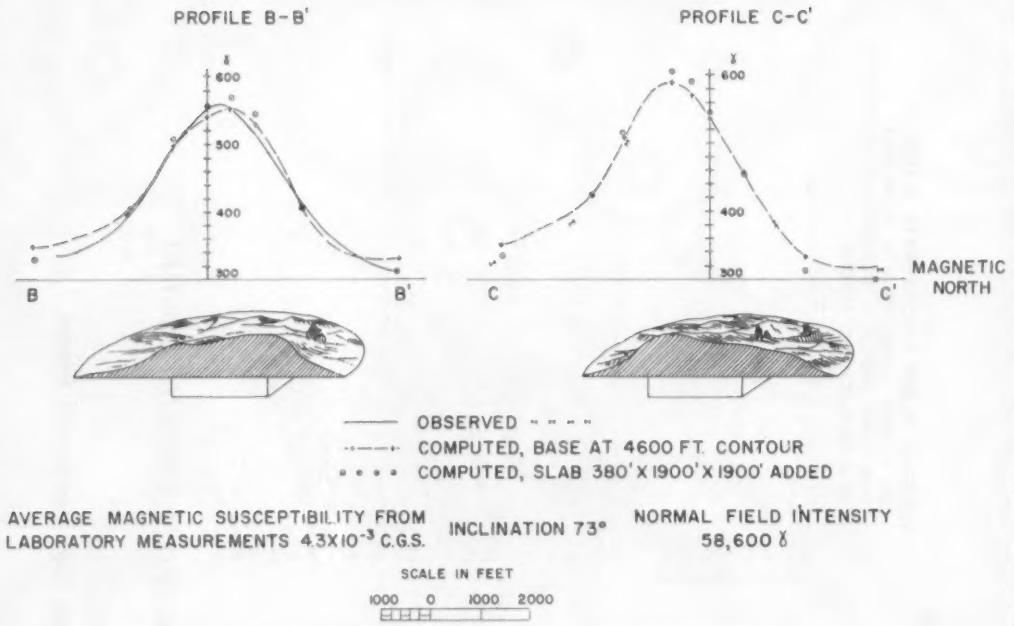


FIG. 9. Computed and observed total-intensity anomaly—Round Butte, Montana.

The inducing field T_0, interpolated from tables by Vestine and others (1945) was 58,600 γ. The calculated values therefore were adjusted to this value of T_0 and susceptibility $k = 0.0043$ cgs by multiplying each by

$$\frac{58{,}600 \times 0.0043}{50{,}000 \times 0.01} = 0.504.$$

The results of the calculation are shown in Figure 9. Observed values along profile *B-B'* are indicated by a solid line. Computed values for the mass shown hachured are indicated by a broken line and crosses. Observed values for profiles *C-C'* are known accurately only at flight line crossings; they are indicated by bars. Unfortunately no flight line passed through the magnetic maximum. In general the mass shown in facsimile accounts rather well for the major part of the observed anomaly. The computed amplitude is somewhat less than that observed, but this is to be expected, as it is unlikely that the laccolith would have the flat base shown with no extension below the 4,600-foot level.

Speculations on the depth extent are affected by all the ambiguities and uncertainties inherent in the magnetic method. In the Round Butte example, however, with the first-order effects reasonably accounted for, it would not be pre-

sumptuous to attempt to set limits to the depth extent. We arbitrarily added a slab 190 feet × 1,900 feet × 1,900 feet having the same susceptibility as the upper material and achieved better agreement with the observed data. We do not claim that this represents the actual situation. The effect of the slab was obtained directly from results of our model experiments. To arrive at an upper limit for the depth extent, the thickness of the slab was increased to 380 feet. The results are shown by the encircled dots for profiles *B-B'* and *C-C'* (Fig. 9). To the extent that the assumptions are justified, the laccolith may very well extend 200 feet below the 4,600-foot level, but hardly more than 400 feet. If on the other hand, the mean susceptibility should be 10 percent less than the value used, the upper limit could be increased to 500 feet. In view of the exposed geometrical configuration it is unlikely that the mean susceptibility would be appreciably greater than the value used.

About two miles east of Round Butte, rising some 1,400 feet above the plain there is a larger igneous mass known as Square Butte. Unlike Round Butte, about 40 percent of the exposed mass is syenite—a syenite of highly variable, and on the average very low, susceptibility. The shonkinite is uniform and has a susceptibility lower than at Round Butte. The aeromagnetic map is shown in Figure 10. Preliminary calculations indicate that the exposed syenite and shonkinite units can account for only 40 percent of the observed anomaly, on the basis of induction theory. Either the mass has a considerable depth extent or it has a very large remanent moment in a direction not too different from the earth's present normal field. Oriented samples were not available for meaningful measurements of the remanent moment. If the remanence has no preferred direction and averages out at the height of the surveying aircraft then induction theory might be applied. In this case, however, the depth extent of the buried mass would seem to be considerable. To resolve the questions at Square Butte, gravity, ground-magnetic, and extensive sampling surveys were made at Square Butte during the summer of 1956.

It can be concluded that accurate and simple calculations of ΔT for theoretical and practical three-dimensional bodies are possible by a transformation of the coordinates of the body followed by Gassmann-type integrations, and that under favorable conditions the determination of the depth extent of finite masses from magnetic data is possible.

ACKNOWLEDGMENTS

William J. Dempsey of the Geological Survey contributed aeromagnetic data and valuable discussion; Donald Marshall and Huntley Ingalls, both of the Geological Survey, supplied calculations on Round and Square Buttes; Kenneth Books and William Johnson of the Geological Survey collected rock specimens.

The authors are grateful to the Geological Museum of Harvard University for the loan of samples for susceptibility measurements; to Rear Admiral W. G. Schindler, Commander of the Naval Ordnance Laboratory, and in particular to

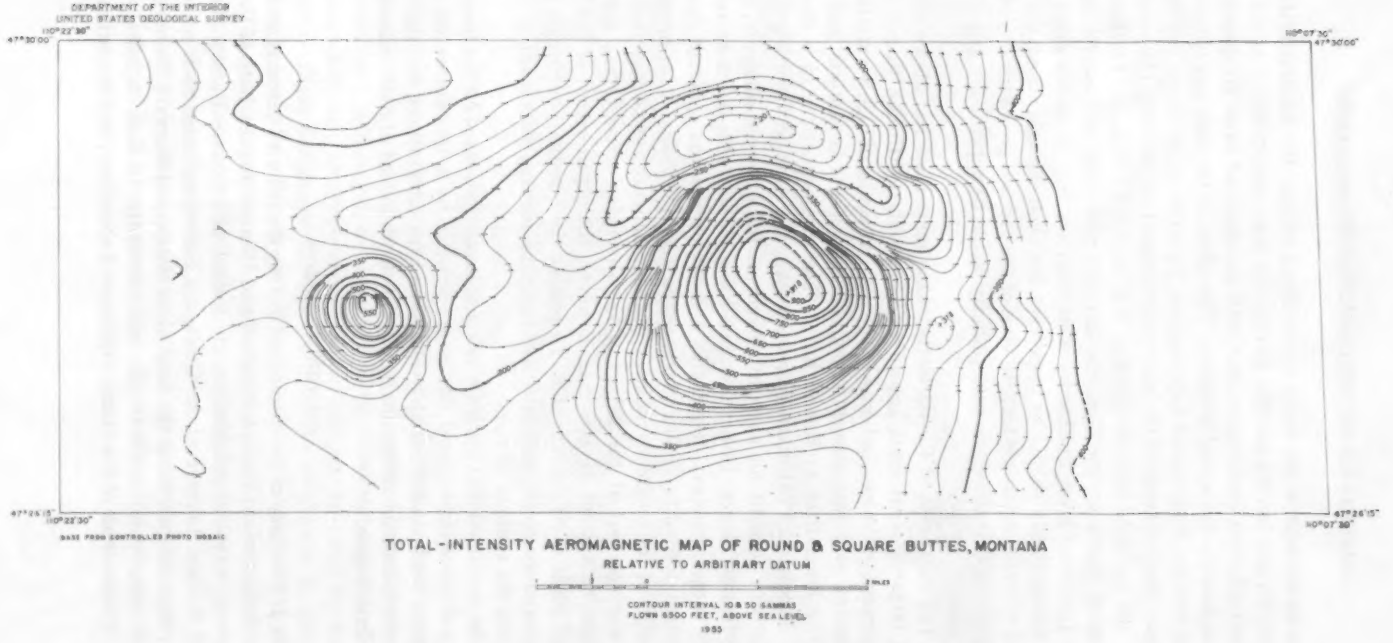


FIG. 10. Total-intensity aeromagnetic map of Round and Square Buttes, Montana.

L. R. Alldredge, formerly of the Electricity and Magnetism Division of the Physics Research Department of the Naval Ordnance Laboratory for the use of facilities in the magnetic model experiments. C. L. Parsons and K. E. Dornstreich, both of the Naval Ordnance Laboratory, gave valuable technical assistance.

APPENDIX

I. *Construction of Integration Charts*

The r, θ integration chart can be constructed with the aid of equation (6) which we write more generally as

$$\Delta T = (2\pi kT_0/c) \iint [\Phi(r, \theta)(3 \cos^2 \theta - 1) \sin \theta/r] dr d\theta. \tag{7}$$

In this expression, c represents the number of circular elements in the integration device. Equation (7) can be replaced by the sum

$$\Delta T = (2\pi kT_0/c) \sum \bar{\Phi}_{ij} \int_{r_i}^{r_{i+1}} \int_{\theta_j}^{\theta_{j+1}} [(3 \cos^2 \theta - 1) \sin \theta/r] dr d\theta \tag{8}$$

where the integration is to be taken over the (i, j)th compartment bounded by arcs of radii r_i and r_{i+1}, and radial lines of angles θ_j and θ_{j+1}. $\bar{\Phi}_{ij}$ is the average value of the concentrate over this compartment. The sum is to be carried over all compartments or parts thereof lying within the boundaries of the concentrate. Carrying out the integration indicated in (8) we have

$$\Delta T = (2\pi kT_0/c) \sum \bar{\Phi}_{ij} \ln \frac{r_{i+1}}{r_i} (\sin^2 \theta_{j+1} \cos \theta_{j+1} - \sin^2 \theta_j \cos \theta_j). \tag{9}$$

The graticule is constructed so that each compartment has the same contribution at point P. Let this constant be some arbitrary value $R < 1$. Then

$$\Delta T = (2\pi kT_0/c) R \sum \bar{\Phi}_{ij} \tag{10}$$

where

$$R = \ln \frac{r_{i+1}}{r_i} (\sin^2 \theta_{j+1} \cos \theta_{j+1} - \sin^2 \theta_j \cos \theta_j). \tag{11}$$

The quantity in parenthesis in (11) must be chosen subject to the condition that it is a submultiple of the first maximum value of the function $\sin^2 \theta \cos \theta$, that is,

$$\sin^2 \theta_{j+1} \cos \theta_{j+1} - \sin^2 \theta_j \cos \theta_j = \frac{0.3849}{n}, \qquad j = 0, 1, 2 \cdots n$$

and n is the number of radial lines between $\theta_0 = 0$ and $\theta_n = 54°44'$. Values of the chart are positive in the range $0 < \theta < \theta_n$, negative in the range $\theta_n < \theta < \pi - \theta_n$, posi-

tive in the range $\pi-\theta_n<\theta<\pi$. The values θ_j for constructing the chart are found by setting $\theta_0=0$ and solving the transcendental equation

$$\sin^2\theta_j\cos\theta_j=\frac{0.3849}{n}\,.$$

From (11)

$$\ln\frac{r_{i+1}}{r_i}=\frac{nR}{0.3849}\,.$$

The radii of concentric semicircles can then be determined in units of an arbitrary constant, r_0, from the formula

$$\ln r_i=\ln r_0+\frac{inR}{0.3849}\qquad i=1,\ 2,\ 3\cdots.$$

The parameters of the charts used in the text of this paper were $k=0.01$ cgs, $T_0=50{,}000\ \gamma$, $c=64$, $R=.00239$ and $n=16$, so that each compartment has the effect of $0.117\bar{\Phi}_{ij}$ gammas at point P. There is nothing unique about this choice of values. They should be chosen to gain sufficient accuracy at minimum computational effort. If c is a submultiple of 360, then an ordinary protractor may be used in the ϕ phase of the integration.

II. *Derivation of formulas* (1) *and* (2)

Let s be a unit vector in the direction of the inducing field T_0, and ξ, η, ζ the coordinates of a point P in a system of coordinates as shown in Figure 1 with the exception that P is not necessarily the origin. The magnetic potential at P of a uniformly magnetized body of susceptibility k is given by

$$\begin{aligned}\Delta V(\xi,\eta,\zeta)&=\iiint kT_0\frac{\partial}{\partial s}\left(\frac{1}{r}\right)dxdydz\\&=k\iiint\left[H_0\frac{\partial}{\partial x}+Z_0\frac{\partial}{\partial z}\right]\left(\frac{1}{r}\right)dxdydz\end{aligned}\qquad(12)$$

where

$$r=[(x-\xi)^2+(y-\eta)^2+(z-\zeta)^2]^{1/2}.$$

See Jeans (1946).

The vertical and horizontal component anomalies are derived from the potential by differentiation.

$$\begin{aligned}\Delta Z&=-\frac{\partial(\Delta V)}{\partial\zeta}\\\Delta H&=-\frac{\partial(\Delta V)}{\partial\xi}.\end{aligned}\qquad(13)$$

In view of (12), 13 and the relations

$$-\frac{\partial\left(\frac{1}{r}\right)}{\partial\zeta} = \frac{\partial\left(\frac{1}{r}\right)}{\partial z} \quad \text{and} \quad -\frac{\partial\left(\frac{1}{r}\right)}{\partial\xi} = \frac{\partial\left(\frac{1}{r}\right)}{\partial x},$$

we have

$$\Delta Z(\xi, \eta, \zeta) = k\iiint\left[H_0\frac{\partial^2}{\partial x\partial z} + Z_0\frac{\partial^2}{\partial z^2}\right]\left(\frac{1}{r}\right)dxdydz$$

$$\Delta H(\xi, \eta, \zeta) = k\iiint\left[H_0\frac{\partial^2}{\partial x^2} + Z_0\frac{\partial^2}{\partial z\partial x}\right]\left(\frac{1}{r}\right)dxdydz. \qquad (14)$$

Carrying out the operations indicated in (14) and taking the origin of coordinates at point P, we have

$$\Delta Z(0, 0, 0) = kZ_0\iiint[(3z^2 - r^2)/r^5]dxdydz$$

$$+ kH_0\iiint(3xz/r^5)dxdydz$$

$$\Delta H(0, 0, 0) = kH_0\iiint[(3x^2 - r^2)/r^5]dxdydz$$

$$+ kZ_0\iiint(3xz/r^5)dxdydz. \qquad (15)$$

The equations (15) are the required equations (1) and (2) of the text.

III. *The two-dimensional case*

With slight modification in use, the well-known polar chart described by Pirson (1940) can be adapted for graphical calculation of total-intensity anomalies of two-dimensional bodies. If the chart in Pirson's Figure 4 is aligned so that its $\Delta\xi$ axis is parallel to the direction H_a in his Figure 2, the total intensity anomaly will be given by

$$\Delta T = \Delta\xi[\cos^2 I \sin^2(\alpha \pm D) + \sin^2 I]^{1/2} \qquad (12)$$

where $\Delta\xi$, H_a, α, and D have the meanings given in Pirson's paper. The radical in (12) is simply the cosine of the angle between H_a in the plane of the profile and T, in the meridianal plane. From equation (12) it is clear that, in this case too, proper orientation of axes results in simplification of calculations.

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GEOPHYSICS, VOL. XXII, NO. 4 (OCTOBER, 1957), PP. 905–921, 7 FIGS.

PROPAGATION OF AN ELECTRIC PULSE THROUGH A HOMOGENEOUS AND ISOTROPIC MEDIUM*

BIMAL KRISHNA BHATTACHARYYA†

ABSTRACT

The paper discusses the propagation of a step-function pulse in a medium characterized by the three electric constants, permittivity ϵ, permeability μ and conductivity σ. The effect of the displacement current on the propagation is fully taken into account. Expressions of electric and magnetic fields are determined. It is shown that the time of travel of the pulse and the initial and final values of any one of the non-vanishing field components (all of which can be measured) fully specify the values of conductivity and permittivity of the medium.

INTRODUCTION

Attempts have been made in recent years to study theoretically the propagation of pulses through a semi-conducting medium (Wait, 1951; Yost, 1952 and Bhattacharyya, 1955, 1957). This has been with a view to exploring the possibilities of utilising the transmission phenomena of electric pulses through the crust of the earth for geophysical prospecting for ore bodies. All these studies are based on the assumption that the displacement current is negligible compared to the conduction current. The question naturally arises: for what range of frequencies and for what specific characteristics of the earth, this assumption is justified.

Displacement currents in the earth are the more important, the higher the permittivity and the resistivity of the earth, and the higher also the frequency. The permittivity of the earth varies between 4 and 40 depending on the nature of the soil. The resistivities of the geologic materials vary greatly from one locality to other. For example, for wet and dry grounds the orders of magnitude of the resistivity are 10^2 to 10^3 metre-ohms and 10^4 to 10^5 metre-ohms respectively. The remaining factor, the frequency (that is, the high frequency content of the pulses) depends upon the shape and repetition frequency of the pulses propagated through the medium. The degree of dependence on frequency may be estimated from the following Table. A comparison is made in the table of the actual propagation constant ($\gamma^2 = -\mu\epsilon\omega^2 + j\mu\sigma\omega$) with the propagation constant for the earth with displacement current neglected ($\gamma'^2 = j\omega\mu\sigma$). The table has been prepared by assuming the following values of the electric constants of the medium:

$$\epsilon = 20\epsilon_0, \qquad \epsilon_0 = \text{dielectric constant of vacuum}$$
$$= 8.854 \times 10^{-12} \text{ farad/metre},$$
$$\text{and} \quad \sigma = 10^{-5} \text{ mhos/metre}.$$

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From the table it is evident that the displacement current can be neglected only when the conductivity of the medium is considerably larger than its permittivity (say, by a factor of 10^5) and the frequency of the electromagnetic waves employed is less than 10 kc/s.

Frequency	10^3 cps	10^3 cps	10^4 cps	10^5 cps	10^6 cps
$\left(\frac{\gamma}{\gamma'}\right)^2 = 1 + j\frac{\omega\epsilon}{\sigma}$	$1 + j0.011$	$1 + j0.11$	$1 + j1.1$	$1 + j11$	$1 + j110$
$\left(\frac{\gamma_0}{\gamma'}\right)^2 = j\frac{\omega\epsilon_0}{\sigma}$	$j5.5 \times 10^{-4}$	$j5.5 \times 10^{-3}$	$j0.055$	$j0.55$	$j5.5$

The high-frequency content of electric pulses with sharp edges and of moderately fast repetition rate (say, 10^3 cps), is, however, normally quite high. Further, the region of the subsurface to be explored electromagnetically, may not satisfy the requirement of high σ/ϵ ratio. These considerations demand that the phenomena of propagation of electric pulses through a semi-conducting medium should be studied taking proper account of the displacement current. As will be seen, such study has the added advantage of providing a possible method of accurately estimating the σ/ϵ ratio of the medium from the results of practical measurement. So far as the author of the present paper is aware, no such study has yet been attempted.

As is generally the case with applied problems, the problem under consideration will be simplified by considering only highly idealised cases. The simplifications introduced will, of course, be such as not to exercise too great an influence on the quantitative results. The simplifications made are as follows:

Firstly, the transmitting antenna is imagined to be of small dimensions. This reduces the problem to the determination of the radiated field due to an electric dipole of length dl, say. It may be noted, however, that the field of an antenna of finite length may be calculated by integration from a superposition of small electric dipoles.

Secondly, the earth is imagined to be isotropic and homogeneous. Hence, the electric properties of the earth are completely characterized by its permeability μ, permittivity ϵ and conductivity σ.

FORMULATION OF THE FIELD EQUATIONS

If the electric dipole be oriented in the z-direction, the general equation of the field may be formulated by introducing the vertically polarized Hertz vector $\overrightarrow{\pi} = (0, 0, \pi_z)$. The Laplace transform of the components of the Hertz vector is given by

$$\pi_z(s) = 0, \qquad \pi_y(s) = 0$$

and

$$\pi_s(s) = \frac{i(s)dl}{4\pi(\sigma + \epsilon s)} \cdot \frac{e^{-\gamma r}}{r} \tag{1}$$

where $i(s)$ is the transform of the current $i(t)$ flowing through the dipole, r is the distance of the point of observation from the dipole and γ is the propagation constant of the medium which is given by

$$\gamma = [\mu(\sigma s + \epsilon s^2)]^{1/2}. \tag{2}$$

In spherical coordinates (r, θ, ϕ), the Hertz vector will be given by

$$\begin{aligned} \vec{\pi}(s) = {} & \frac{i(s)dl}{4\pi(\sigma + \epsilon s)} \cdot \frac{e^{-\gamma r}}{r} \cos\theta \cdot \vec{i}_r \\ & - \frac{i(s)dl}{4\pi(\sigma + \epsilon s)} \cdot \frac{e^{-\gamma r}}{r} \sin\theta \cdot \vec{i}_\theta. \end{aligned} \tag{3}$$

The electric and magnetic field vectors are related to the Hertz vector in the following way.

$$\vec{e}(s) = \text{grad div } \vec{\pi}(s) - \gamma^2 \vec{\pi}(s) \tag{4}$$

$$\vec{h}(s) = (\sigma + \epsilon s) \text{ curl } \vec{\pi}(s) \tag{5}$$

Hence the non-vanishing electric and magnetic field components may be expressed as

$$e_r(s) = \frac{i(s)dl}{2\pi(\sigma + \epsilon s)} \cdot \frac{e^{-\gamma r}}{r^3} \cdot (1 + \gamma r) \cos\theta \tag{6}$$

$$e_\theta(s) = \frac{i(s)dl}{4\pi(\sigma + \epsilon s)} \cdot \frac{e^{-\gamma r}}{r^3} \cdot (1 + \gamma r + \gamma^2 r^2) \cdot \sin\theta \tag{7}$$

and

$$h_\phi(s) = \frac{i(s)dl}{4\pi r^2} \cdot e^{-\gamma r} \sin\theta \cdot (1 + \gamma r). \tag{8}$$

A STEP-FUNCTION CURRENT SOURCE

When a step-function current (Fig. 1) of amplitude I is passing through the dipole, $i(s)$ is given by

$$i(s) = \frac{I}{s}. \tag{9}$$

Substituting (2) and (9) into (6), we obtain

$$e_r(s) = \frac{Idl\cos\theta}{2\pi r^3} \cdot \frac{e^{-\sqrt{\mu\sigma s + \mu\epsilon s^2} \cdot r}}{(\sigma s + \epsilon s^2)} \cdot [1 + \sqrt{\mu\sigma s + \mu\epsilon s^2} \cdot r]. \tag{10}$$

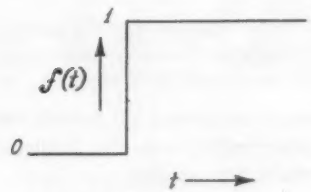

FIG. 1. A step-function type of pulse.

Similar expressions may be obtained for the other two field components, e.g., $e_\theta(s)$ and $h_\phi(s)$.

If we assume $\epsilon = 0$ in these expressions, we readily obtain equations which have been solved by Wait (1951) and Bhattacharyya (1957). We have already discussed the limitations of the analysis based on this assumption and hence, we shall attempt to solve equations (6)–(8) in the most general case where the effect of displacement current is not negligible. With this purpose in view, let us rewrite equation (10) in the following form:

$$e_r(s) = \frac{Idl\cos\theta}{2\pi r^3}\,\frac{e^{-\sqrt{\mu\epsilon}\cdot r\cdot\sqrt{s^2+\sigma s/\epsilon}}}{(\sigma s+\epsilon s^2)}\cdot\left[1+\sqrt{\mu\sigma s+\mu\epsilon s^2}\cdot r\right]. \tag{11}$$

In (11), $\sqrt{\mu\epsilon}\cdot r$ is the time required by the propagating pulse to reach the point of observation. As such, the time τ at which the propagated pulse may be recorded at the point of observation, is necessarily greater than $\sqrt{\mu\epsilon}\cdot r$. With this fact in mind, let us rewrite (11) with the substitutions

$$t \equiv \frac{\tau}{\sqrt{\mu\epsilon}\cdot r}, \qquad e_r(s) \equiv \frac{2\pi r^2 e_r(s)}{Idl\cos\theta}\cdot\sqrt{\frac{\epsilon}{\mu}} \quad \text{and} \quad b = \sigma r\sqrt{\frac{\mu}{\epsilon}}.$$

It can now be easily shown that b is a dimensionless parameter. Then we have

$$e_r(s) = \frac{e^{-\sqrt{s^2+bs}}}{(s^2+bs)}\cdot\left[1+\sqrt{s^2+bs}\right]. \tag{12}$$

Substitution of

$$t \equiv \frac{\tau}{\sqrt{\mu\epsilon}\cdot r} \quad \text{and} \quad e_\theta(s) \equiv \frac{e_\theta(s)\cdot 4\pi r^2}{Idl\sin\theta}\cdot\sqrt{\frac{\epsilon}{\mu}}$$

into (7) will give the following expression for $e_\theta(s)$:

$$e_\theta(s) = \frac{e^{-\sqrt{s^2+bs}}}{(s^2+bs)}\cdot\left[1+\sqrt{s^2+bs}+(s^2+bs)\right]. \tag{13}$$

Similarly, the following substitutions may be made into (8)

$$t \equiv \frac{\tau}{\sqrt{\mu\epsilon}\cdot r} \quad \text{and} \quad h_\phi(s) \equiv \frac{4\pi r^2 h_\phi(s)}{Idl \sin\theta}$$

to obtain

$$h_\phi(s) = \frac{e^{-\sqrt{s^2+bs}}}{s}\cdot\left[1 + \sqrt{s^2+bs}\right]. \tag{14}$$

The time t appearing in the expressions which are inverse transforms of the field equations (12)–(14), must be greater than 1.

It will be convenient if we now consider equations (12)–(14) one by one and determine the expressions of the field components as functions of time and electric constants of the medium.

Expression for $e_r(t)$

Evaluation of the inverse transform of (12) will yield (Appendix I):

$$e_r(t) = e^{-bt/2}\cdot I_0\left[\frac{b}{2}\cdot(t^2-1)^{1/2}\right] + \frac{1}{b}\left(1 - e^{-bt}\right) - e^{-bt/2}\int_0^1 I_0\left[\frac{b}{2}(t^2-x^2)^{1/2}\right]dx, \quad (t>1). \tag{15}$$

In Appendix I, $e_r(t)$ has been expressed as a function of b and t [equations (ix), (xi) and (xii)]. Equation (ix) has been utilised to plot the curve of $e_r(t)$ versus t with b as a parameter (Figs. 2–5). It is well to recall here that the normalised time t is equivalent to

$$\frac{\tau \text{ (in seconds)}}{\sqrt{\mu\epsilon}\cdot r \text{ (in seconds)}}.$$

From the definition of b it is clear that values of b actually specify the ratio of conductivity and permittivity of the medium, since at a particular distance, $\sqrt{\mu\epsilon}\cdot r$ is a constant. Four values of b have been chosen to plot the curves in Figures 2–5.

In all the figures we observe that the radial electric field has initially a finite value and approaches a steady value asymptotically with the increase of time. The initial and final values are dependent upon b and, as shown in Appendix II [Equations (xviii) and (xix)], are given by

$$e_r(t)\big|_{t=1} = e^{-b/2} \tag{16}$$

and

$$\lim_{t\to\infty} e_r(t) = \frac{1}{b}. \tag{17}$$

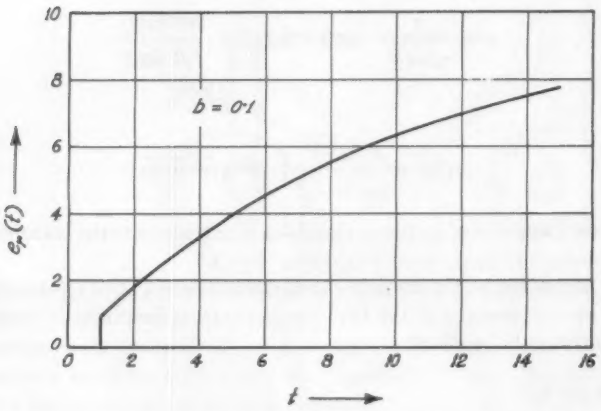

FIG. 2. Plot of $e_r(t)$ against time for $b=0.1$.

Equations (16) and (17) have been plotted in Figure 6. This figure indicates that the initial and final values of $e_r(t)$ are attenuated rapidly with the increase in b. We know that as the conductivity of a medium increases in proportion to the permittivity, i.e., as b increases, the attenuation constant of a medium will increase

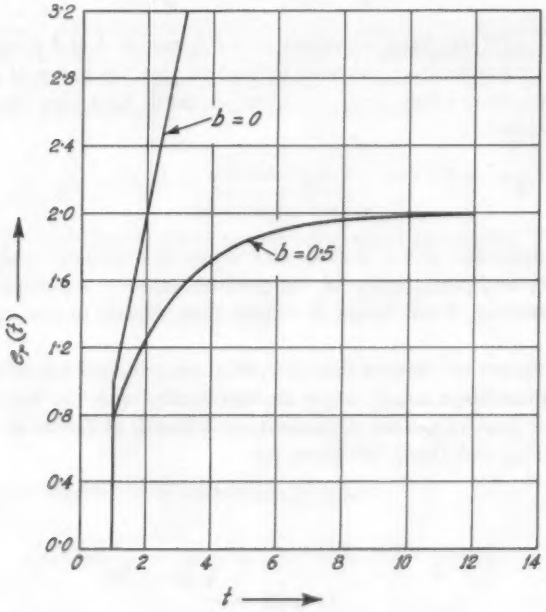

FIG. 3. Plot of $e_r(t)$ against time for $b=0$ and $b=0.5$.

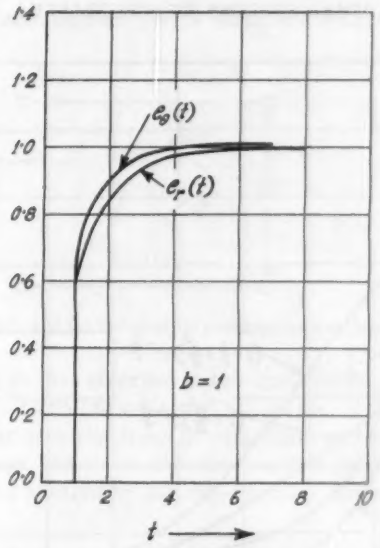

FIG. 4. Plot of $e_r(t)$ and $e_\theta(t)$ against time for $b = 1$.

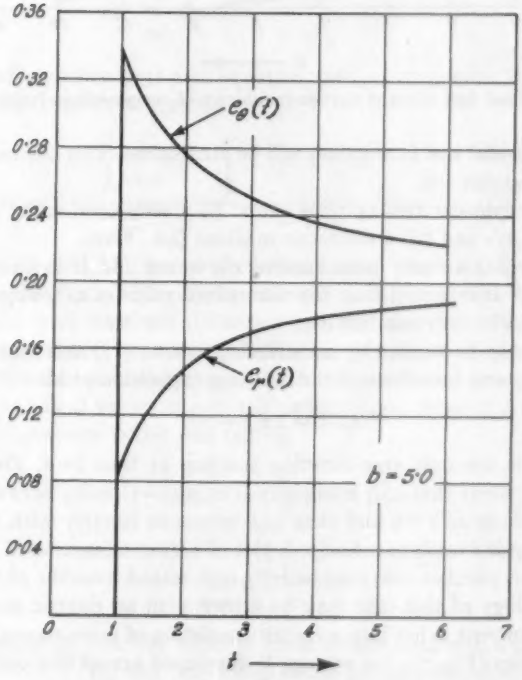

FIG. 5. Plot of $e_r(t)$ and $e_\theta(t)$ against time for $b = 5.0$.

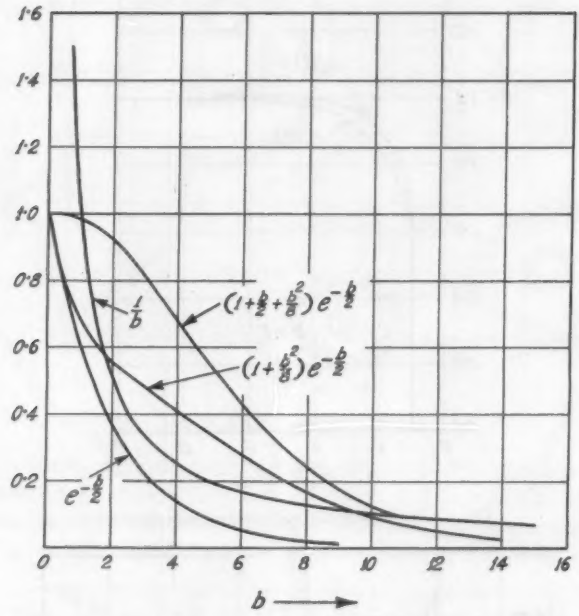

FIG. 6. Initial and final values of the non-vanishing field components as function of time.

and hence the initial and final values will be diminished. This has been substantiated by the diagrams 2–6.

Let us now consider two extreme cases: (i) a semi-conducting medium with large values of σ/ϵ and (ii) a dielectric medium (i.e., $b=0$).

The former has already been treated elsewhere and it is known that $e_r(t)$ starts from zero at $t=0$ and then the normalised value of $e_r(t)$ approaches unity asymptotically with increase in time.

The latter may be studied by substituting $b=0$ in (12) and then the determination of the inverse transform of the resulting expression yields:

$$e_r(t) = t\,u(t-1), \tag{18}$$

where $u(t-1)$ is the unit step-function starting at time $t=1$. From (16), (17) and (18) it is evident that $e_r(t)$ is initially (i.e., at $t=1$) unity because there is no loss in the medium as $\sigma=0$ and then $e_r(t)$ increases linearly with time, tending towards infinity as t tends to infinity. A plot of $e_r(t)$ as a function of time is shown in Figure 3. This peculiar case may be fully understood from the physical point of view if an analogy of this case may be drawn with an electric circuit. When a step-function current is fed into a circuit consisting of a resistance R and a condenser C in series (Fig. 7), the voltage V developed across this combination will

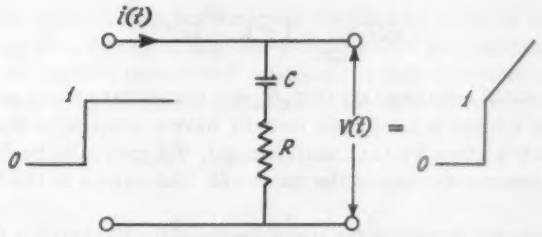

FIG. 7. An *RC*-circuit and the nature of its response to a step-function input pulse.

be of a nature similar to that observed in this case. Initially, the condenser will behave as a short-circuit and the voltage V will be the iR-drop across the resistance. Then V will begin to rise linearly with time, as the condenser is being charged up. In this case, the whole dielectric medium may be thought of as an electric condenser being charged by the step-function current source.

Expression for $e_\theta(t)$

Substituting (12) into (13), we have

$$e_\theta(s) = e_r(s) + e^{-\sqrt{s^2+bs}}. \tag{19}$$

With the aid of equation (15) and equation (xxi) of Appendix III, the inverse transform of $e_\theta(s)$ may be written as

$$e_\theta(t) = e_r(t) + \frac{be^{-bt/2}}{2} \cdot \frac{I_1\left[\frac{b}{2}(t^2-1)^{1/2}\right]}{(t^2-1)^{1/2}}, \qquad (t > 1). \tag{20}$$

For small values of b, the second expression in (20) which will be henceforward denoted by $\phi(t)$, has but a negligible contribution to $e_\theta(t)$ and hence, the nature of variation of $e_\theta(t)$ with time will differ but a little from that of $e_r(t)$. For large values of b, however, $\phi(t)$ has a marked effect on the nature of $e_\theta(t)$. Plots of $e_\theta(t)$ versus t have been shown in Figures 4 and 5 for two values of b, e.g., 1.0 and 5.0.

The initial and final values of $e_\theta(t)$ will depend upon those of $\phi(t)$. Now, from Appendix III [Equations (xxiii) and (xxiv)],

$$\phi(t)\Big|_{t=1} = \frac{b^2}{8} e^{-b/2} \tag{21}$$

and

$$\lim_{t\to\infty} \phi(t) = 0. \tag{22}$$

So the final value of $e_\theta(t)$ for any value of b will be identical with that of $e_r(t)$, i.e., $1/b$. A combination of (16) and (21) will give the initial value of $e_\theta(t)$.

$$e_\theta(t)\Big|_{t=1} = \left(1 + \frac{b^2}{8}\right)e^{-b/2}. \tag{23}$$

From the plot of equation (23) (Fig. 6), it is found that so long as b lies, within approximately 1.7 and 9.5, $e_\theta(t)$ will initially have a steep pulse front, the magnitude of which is given by (23), and then $e_\theta(t)$ will gradually begin to decrease with time to assume ultimately the value $1/b$. The nature of the fall of $e_\theta(t)$ is concave.

When b does not lie within the above limits, $e_\theta(t)$ will assume a final value always greater than its initial value. The nature of rise of $e_\theta(t)$ with time is convex.

If the magnitude of displacement current is negligible compared to that of conduction current, we know that the curve of $e_\theta(t)$ will start from zero at $t=0$ and will have overshoot.

In case, the medium is a non-conducting one, the nature of $e_\theta(t)$ will resemble that of $e_r(t)$ since $\phi(t)=0$, for $t>1$.

Expression for $h_\phi(t)$

From Appendix IV [equation (xxxi)],

$$h_\phi(t) = \left(1 + \frac{b}{2} + \frac{b^2}{8}\right)e^{-b/2} - \frac{b}{2}\int_1^t e^{-bt/2}\left[\frac{\partial}{\partial x}\cdot\frac{I_1\left(\frac{b}{2}\sqrt{t^2-x^2}\right)}{\sqrt{t^2-x^2}}\right]_{x=1} dt. \tag{24}$$

The curve of $h_\phi(t)$ with time may be plotted by integrating the last integral of (24) numerically.

The initial and final values of $h_\phi(t)$ are given by [equations (xxxii) and (xxxiii)].

$$h_\phi(t)\Big|_{t=1} = \left(1 + \frac{b}{2} + \frac{b^2}{8}\right)e^{-b/2} \tag{25}$$

and

$$\lim_{t\to\infty} h_\phi(t) = 1. \tag{26}$$

A plot of the initial value against time is included in Figure 6. It is evident from the diagram that the initial value can never exceed the final value. With the increase in b, $h_\phi(t)$ at $t=1$ begins to decrease slowly for $b<2$ and rapidly for $b>2$.

DISCUSSION

The results obtained above may have useful applications in the work of geophysical exploration. For example, one can determine the constants σ and ϵ of the

medium under study from a knowledge of the time of travel of the pulse and of the initial and final values of the non-vanishing field components, e_r, e_θ and h_ϕ. Thus, using actual (not normalised) values of the field components, and employing subscripts i and f to denote initial and final values, we may write

$$\frac{e_{ri}}{e_{rf}} = \frac{\sigma}{\epsilon} t_1 \cdot e^{-\sigma/\epsilon \cdot t_1/2}, \tag{27}$$

$$\frac{e_{\theta i}}{e_{\theta f}} = \frac{\sigma}{\epsilon} t_1 \left(1 + \frac{1}{8} \frac{\sigma^2}{\epsilon^2} t_1^2\right) e^{-\sigma/\epsilon \cdot t_1/2} \tag{28}$$

and

$$\frac{h_{\phi i}}{h_{\phi f}} = \left(1 + \frac{\sigma t_1}{2\epsilon} + \frac{\sigma^2 t_1^2}{8\epsilon}\right) e^{-\sigma/\epsilon \cdot t_1/2} \tag{29}$$

where $t_1 = \sqrt{\mu\epsilon} \cdot r$ = time of travel of the electric pulse from the source to the point of observation.

Rearranging equations (27) and (28), we get

$$\frac{\sigma}{\epsilon} = \frac{2}{t_1} \sqrt{2\left(\frac{e_{\theta i}}{e_{\theta f}} \cdot \frac{e_{rf}}{e_{ri}} - 1\right)} \tag{30}$$

The ratio σ/ϵ can be obtained directly from equation (30) if the initial and final values of e_r and e_θ are known from practical measurement. The method, however, involves the measurement of four parameters.

The value of $t_1 = \sqrt{\mu\epsilon} \cdot r$ can be experimentally observed. Knowing the distance r and remembering that the permeability of the crust of the earth is nearly the same as that of vacuum, i.e., 1.257×10^{-6} henry/metre, the magnitude of ϵ, the permittivity of the medium, can be easily calculated. Once this is found out, σ can be directly obtained from equation (30).

It will be noted that the value of σ can be also obtained from any of the equations (27), (28) and (29), if the initial and final values of any one of the three field components are known. Thus the disadvantage of measuring four parameters involved in equation (30) can be avoided.

It has been observed in course of this study that the field at any point assumes initially a finite value, unless the effect of displacement current is negligible. The magnitude of the dimensionless parameter b $(= \sigma r \sqrt{\mu/\epsilon})$ actually determines the initial and steady values of the field.

To obtain a better idea of the dependence of σ/ϵ on the magnitude of b, and thus the effect of σ/ϵ on the values of the field, we may work out a typical numerical example. Let 1 μsec. be the time required by the electromagnetic wave to travel to a distant point r from the source where the field is measured. Then, since $\sqrt{\mu\epsilon} \cdot r = 10^{-6}$ sec,

$$b = \frac{\sigma}{\epsilon} \times 10^{-6}.$$

This shows that if $b=1$, the ratio σ/ϵ is equal to 10^6, a very large value. Nevertheless, for a step-function input, the displacement current has a distinct effect on the field, as is evident from Figure 4. This is explained by the fact that the high-frequency content of the step-function pulse is quite large.

The analysis presented in this paper has been made specially for a step-function source. The equations deduced may, however, be used for obtaining the field expressions for other types of pulses.

ACKNOWLEDGEMENTS

It is a pleasure to record grateful thanks to Prof. S. K. Mitra for helpful discussions during the progress of the work. The author is also grateful to Dr. J. N. Bhar, D.Sc., F.N.I., Head of the Department of Radio Physics and Electronics, University of Calcutta, for his keen interest in the work.

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APPENDIX

I. *Inverse transform of* $e_r(s)$

$e_r(s)$ may be written as:

$$e_r(s) = \frac{e^{-x\sqrt{s^2+bs}}}{(s^2+bs)} + \frac{e^{-x\sqrt{s^2+bs}}}{\sqrt{s^2+bs}}. \qquad \text{(i)}$$

From a table of Laplace transforms (Campbell & Foster, 1948), we obtain

$$\frac{e^{-x(s^2+bs)^{1/2}}}{(s^2+bs)^{1/2}} \equiv e^{-bt/2} I_0\left[\frac{b}{2}(t^2-x^2)^{1/2}\right], \quad (t>x) \qquad \text{(ii)}$$

where I_0 is the modified Bessel function of the first kind and of order zero. Integration of (ii) with respect to x from 0 to x yields

$$\frac{e^{-x(s^2+bs)^{1/2}}}{(s^2+bs)} - \frac{1}{(s^2+bs)} \equiv -e^{-bt/2}\int_0^x I_0\left[\frac{b}{2}(t^2-x^2)^{1/2}\right]dx, \quad (t>x). \qquad \text{(iii)}$$

Hence,

$$\frac{e^{-x(s^2+bs)^{1/2}}}{(s^2+bs)} \equiv \frac{1}{b}(1-e^{-bt}) - e^{-bt/2}\int_0^x I_0\left[\frac{b}{2}(t^2-x^2)^{1/2}\right]dx, \quad (t>x). \qquad \text{(iv)}$$

Now, with the aid of (ii) and (iv), we may write the inverse transform of (i) in

the following way:

$$e_r(t) = e^{-bt/2} I_0\left[\frac{b}{2}(t^2-1)^{1/2}\right] + \frac{1}{b}(1-e^{-bt}) - e^{-bt/2}\int_0^1 I_0\left[\frac{b}{2}(t^2-x^2)^{1/2}\right]dx, \qquad (t>1). \tag{v}$$

The integral in (v) cannot be expressed in any closed form and so the values of the integral may be determined at successive instants either by taking recourse to numerical integration or by expressing the above integral in the form of a convergent series of time. The latter method is more convenient than the former for values of $t>2$, so far as quick and sufficiently accurate evaluation of the integral is concerned.

Let us now consider the argument of the modified Bessel function which can be expanded in the following way:

$$\frac{b}{2}(t^2-x^2)^{1/2} - \frac{bt}{2}(1-X) \tag{vi}$$

where

$$X = \frac{1}{2}\cdot\frac{x^2}{t^2} + \frac{1}{8}\cdot\frac{x^4}{t^4} + \frac{1}{16}\cdot\frac{x^6}{t^6} + \frac{5}{128}\cdot\frac{x^8}{t^8} + \frac{7}{256}\cdot\frac{x^{10}}{t^{10}} + \cdots. \tag{vii}$$

An expansion of the modified Bessel function in Taylor's series will now yield

$$I_0\left[\frac{bt}{2}(1-X)\right] = I_0\left(\frac{bt}{2}\right) - \frac{bt}{2}\cdot X\cdot I_0'\left(\frac{bt}{2}\right) + \frac{X^2}{2!}\cdot\frac{b^2t^2}{2^2} I_0''\left(\frac{bt}{2}\right) - \cdots. \tag{viii}$$

where $I_0^{(v)}(bt/2)$ is the vth successive derivative of $I_0(bt/2)$ with respect to $(bt/2)$. The next step will be to substitute the value of X from (vii) to (viii) and then integrate (viii) with respect to x within the limits $x=0$ to $x=1$. The series thus obtained will be substituted into (v) and then we have,

$$\begin{aligned} e_r(t) = {} & e^{-bt/2}\cdot I_0\left[\frac{b}{2}(t^2-1)^{1/2}\right] + \frac{1}{b}(1-e^{-bt}) \\ & - e^{-bt/2} I_0\left(\frac{bt}{2}\right) + e^{-bt/2}\cdot\frac{b}{2}\left[\frac{1}{6t} + \frac{1}{40t^3} + \frac{1}{112t^5} + \cdots\right] I_1\left(\frac{bt}{2}\right) \\ & - e^{-bt/2}\cdot\frac{b^2}{8}\left[\frac{1}{20t^2} + \frac{1}{56t^4} + \frac{5}{9.64}\cdot\frac{1}{t^6} + \cdots\right]\cdot\left[I_0\left(\frac{bt}{2}\right) - \frac{2}{bt}\cdot I_1\left(\frac{bt}{2}\right)\right] \\ & + e^{-bt/2}\cdot\frac{b^3}{48}\left[\frac{1}{56t^3} + \frac{1}{96t^5} + \cdots\right]\left[\left\{1 + \frac{8}{(bt)^2}\right\} I_1\left(\frac{bt}{2}\right) - \frac{2}{bt} I_0\left(\frac{bt}{2}\right)\right] \\ & - \cdots, \qquad (t>1). \end{aligned} \tag{ix}$$

In the derivation of (ix), the following formulae have been utilised:

$$I_0'(x) = I_1(x) \quad \text{and} \quad I_1'(x) = I_0(x) - \frac{I_1(x)}{x}. \tag{x}$$

From (ix) it is evident that for $t > 2$, the higher order terms in $(1/t)$ may be neglected.

Sometimes, for special values of b and t, the following expansions may be helpful in numerical computation of $e_r(t)$:

$$\begin{aligned}(1)\quad e_r(t) = {} & \frac{1}{b}(1 - e^{-bt}) - \frac{2}{3!}\, b^{1/2} \cdot \frac{1}{2\sqrt{\pi}} \cdot t^{-3/2} \\ & + \left(\frac{1}{3!} \cdot \frac{1}{b^{1/2}} + \frac{4}{5!}\, b^{3/2}\right) \cdot \frac{3}{4\sqrt{\pi}}\, t^{-5/2} \\ & - \left(-\frac{1}{4.3!} \cdot \frac{1}{b^{3/2}} + \frac{6}{5!}\, b^{1/2} + \frac{6}{7!}\, b^{5/2}\right) \cdot \frac{15}{8\sqrt{\pi}} \cdot t^{-7/2} \\ & + \left(\frac{1}{8.3!} \cdot \frac{1}{b^{5/2}} + \frac{3}{2.5!} \cdot \frac{1}{b^{1/2}} + \frac{15}{7!}\, b^{3/2} + \frac{8}{9!}\, b^{7/2}\right) \cdot \frac{105}{16\sqrt{\pi}} \cdot t^{-9/2} \\ & - \cdots, \qquad (t > 1).\end{aligned} \tag{xi}$$

This equation has been obtained by expanding (i) in higher order terms of $s^{1/2}$.

$$\begin{aligned}(2)\quad e_r(t) = {} & \frac{1}{b}(1 - e^{-bt}) + \left[-\frac{b^2}{4.3!} + \frac{12b^4}{128.5!} - \frac{30b^6}{1024.7!} + \cdots\right] \\ & + \left[\frac{b^3}{8.3!} - \frac{12b^5}{256.5!} + \frac{30b^7}{2048.7!} - \frac{35b^9}{2^{13} \cdot 9!} + \cdots\right] t \\ & + \left[-\frac{5b^4}{64.3!} + \frac{28b^6}{1024.5!} - \frac{270b^8}{16.2048.7!} + \cdots\right] \cdot \frac{t^2}{2!} \\ & + \cdots, \qquad (t > 1).\end{aligned} \tag{xii}$$

This equation is obtained by expanding (i) in decreasing powers of s.

II. *Initial and Final values of the field components*

If $f(s)$ denotes the inverse Laplace transform of $\phi(t)\, u(t)$, it is known that

$$\lim_{|s| \to 0} sf(s) = \lim_{t \to \infty} \phi(t) u(t) \tag{xiii}$$

and

$$\lim_{|s| \to \infty} sf(s) = \lim_{t \to 0} \phi(t) u(t) \tag{xiv}$$

where $u(t)$ denotes a step-function starting at time $t=0$. When the time-function is defined as

$$F(t) = \phi(t-1)u(t-1), \qquad t > 1$$
$$= 0, \qquad t < 1$$

the initial and final values can be determined with the help of (xiii) and (xiv) by a translation of time from $t=1$ to $t=0$. Then we have

$$F(t)\,|_{t=\infty} = \lim_{|s|\to 0} se^{s}f(s) \tag{xv}$$

and

$$F(t)\,|_{t=1} = \lim_{s\to\infty} se^{s}f(s). \tag{xvi}$$

In the case of $e_r(t)$, we have

$$se^{s}e_r(s) = \frac{e^{-\sqrt{s^2+bs}}\cdot(1+\sqrt{s^2+bs})}{(s+b)}. \tag{xvii}$$

As $|s|$ tends to zero, from (vii) it is practically evident that $s\cdot e^{s}\cdot e_r(s)$ tends to $1/b$. So

$$\underset{t\to\infty}{Lt}\ e_r(t) = \frac{1}{b}. \tag{xviii}$$

This gives the steady value of the radial electric field. In order to determine the initial value, we may express (xvii) in the following form:

$$\underset{s\to\infty}{Lt}\ se^{s}e_r(s)$$
$$= \underset{s\to\infty}{Lt}\left[\frac{1}{s+b}+\sqrt{\frac{s}{s+b}}\right]\exp\left[-\frac{b}{2}+\frac{b^2}{8s}-\frac{b^3}{16s^2}+\cdots\right] \tag{xix}$$
$$= \exp\left(-\frac{b}{2}\right).$$

III. *Inverse transform of* $\phi(s)$

Differentiating both sides of (ii) with respect to x, we have

$$e^{-x(s^2+bs)^{1/2}} - e^{-x(s+b/2)} \equiv \frac{bx}{2}\cdot e^{-bt/2}\cdot\frac{I_1\left[\frac{b}{2}(t^2-x^2)^{1/2}\right]}{(t^2-x^2)^{1/2}}, \tag{xx}$$

where I_1 is the first order modified Bessel function. Putting $x=1$ in (xx) and noting that the second term in the left hand side of (xx) gives rise to impulsive

function at $t=1$, we obtain

$$e^{-(s^2+bs)^{1/2}} \equiv \frac{b}{2}\cdot e^{-bt/2}\cdot\frac{I_1\left[\frac{b}{2}(t^2-1)^{1/2}\right]}{(t^2-1)^{1/2}}\cdot \qquad \text{(xxi)}$$

$$= \phi(t), \qquad (t>1)$$

The value of $\phi(t)$ at $t=1$ may be obtained by an expansion of (xxi) in the following way:

$$\phi(t) = \frac{b}{2}\cdot\frac{e^{-bt/2}}{(t^2-1)^{1/2}}\left[\frac{1}{2}\cdot\frac{b}{2}(t^2-1)^{1/2}+\frac{1}{2^3\cdot 1!\cdot 2!}\cdot\frac{b^3}{8}(t^2-1)^{3/2}+\cdots\right] \qquad \text{(xxii)}$$

So

$$\phi(t)\Big|_{t=1} = \frac{b^2}{8}e^{-b/2}. \qquad \text{(xxiii)}$$

It can now be easily proved that

$$\lim_{t\to\infty}\phi(t) = 0. \qquad \text{(xxiv)}$$

IV. *Inverse transform of* $h_\phi(s)$

The expression of $h_\phi(s)$ (14) can be rewritten in the form:

$$h_\phi(s) = \frac{e^{-\sqrt{s^2+bs}}}{s}+\frac{e^{-\sqrt{s^2+bs}}\cdot\sqrt{s^2+bs}}{s}\cdot \qquad \text{(xxv)}$$

With the help of the theory of Laplace transform, it may be stated that if

$$\phi(p) \equiv e^{-bt/2}f\left[\frac{b}{2}(t^2-x^2)^{1/2}\right], \qquad (t>x) \qquad \text{(xxvi)}$$

then

$$\frac{\phi(p)}{p} \equiv \int_x^t e^{-bt/2}f\left[\frac{b}{2}(t^2-x^2)^{1/2}\right]dt, \qquad (t>x). \qquad \text{(xxvii)}$$

Application of the above formulae in (xx) gives

$$\frac{e^{-x(s^2+bs)^{1/2}}}{s} \equiv e^{-(b/2)x}+\frac{bx}{2}\int_x^t e^{-bt/2}\cdot\frac{I_1\left[\frac{b}{2}\sqrt{t^2-x^2}\right]}{\sqrt{t^2-x^2}}dt, \quad (t>x). \qquad \text{(xxviii)}$$

Differentiating (xxviii) with respect to x and applying the theorem

$$\frac{\partial}{\partial x}\int_x^t f(x,t)dt = -f(x,x) + \int_x^t \frac{\partial f(x,t)}{\partial x}\,dt, \tag{xxix}$$

we obtain

$$\frac{e^{-x(s^2+bs)^{1/2}}}{s}(s^2+bs)^{1/2} \equiv \frac{b}{2}e^{-bx/2} - \frac{b}{2}\int_x^t e^{-bt/2}\cdot\frac{I_1\left(\frac{b}{2}\sqrt{t^2-x^2}\right)}{\sqrt{t^2-x^2}}\,dt$$
$$-\frac{bx}{2}\int_x^t e^{-bt/2}\cdot\left[\frac{\partial}{\partial x}\cdot\frac{I_1\left(\frac{b}{2}\sqrt{t^2-x^2}\right)}{\sqrt{t^2-x^2}}\right]dt \tag{xxx}$$
$$+\frac{bx}{2}\cdot e^{-bt/2}\cdot\frac{I_1\left(\frac{b}{2}\sqrt{t^2-x^2}\right)}{\sqrt{t^2-x^2}}\Bigg|_{t=x}.$$

A combination of equations (xxviii) and (xxx) will yield

$$h_\phi(t) = \left(1+\frac{b}{2}+\frac{b^2}{8}\right)e^{-b/2}$$
$$-\frac{b}{2}\int_1^t e^{-bt/2}\cdot\left[\frac{\partial}{\partial x}\,\frac{I_1\left(\frac{b}{2}\sqrt{t^2-x^2}\right)}{\sqrt{t^2-x^2}}\right]_{x=1}dt \tag{xxxi}$$

It can now be easily shown that

$$h_\phi(t)\Big|_{t=1} = \left(1+\frac{b}{2}+\frac{b^2}{8}\right)e^{-b/2} \tag{xxxii}$$

and

$$\underset{t\to\infty}{Lt}\ h_\phi(t) = 1. \tag{xxxiii}$$

GEOPHYSICS, VOL. XXII, NO. 4 (OCTOBER, 1957), PP. 922–931, 4 FIGS.

COMMITTEE ON MAGNETIC RECORDING

REPORT OF SUBCOMMITTEE ON DEFINITIONS AND MEASUREMENTS

ORGANIZATION

On June 28, 1954 the SEG Committee for the Standardization of Magnetic Recording of Seismic Signals set up a subcommittee to work on the problem of establishing definitions and measurement procedures to be used in specifying characteristics of magnetic recording equipment. Mr. William E. N. Doty with the Geophysical Division, Development and Research Department of Continental Oil Company, Ponca City, Oklahoma, was asked to assume chairmanship. The membership was as follows:

William E. N. Doty
Continental Oil Company
Ponca City, Oklahoma

R. A. Arnett
Houston Technical Laboratories
Houston, Texas

Roger Harlan
Southwestern Engineering and Equipment Company
Dallas, Texas

Frank Coker
United Geophysical Corporation
Pasadena, California

Robert Kelley
Texas Instrument Company
Dallas, Texas

Louis W. Erath
Southwestern Industrial Electronics
Houston, Texas

L. B. McManis
Stanolind Oil and Gas Company
Tulsa, Oklahoma

Robert C. Moody
Techno Instrument Company
Los Angeles, California

On October 3, 1955 at the fourth meeting of the SEG Committee on Standardization of Magnetic Recording of Seismic Signals, Mr. L. W. Erath, Vice President in charge of the Research Department of Southwestern Industrial Electronics, Houston, Texas, assumed chairmanship of the subject subcommittee from Mr. William E. N. Doty. Members are listed below:

L. W. Erath
Southwestern Industrial Electronics
Houston, Texas

J. M. Cunningham
Techno Instrument Company
Los Angeles, California

J. J. DuRapau*
E. B. Tickell*
Technical Instrument Company
Houston, Texas

* Alternates.

Frank J. Feagin
Humble Oil and Refining Company
Houston, Texas

Harold Frank
Electro-Technical Labs, Inc.,
Houston, Texas

Robert Kelley
Houston Technical Laboratories
Houston, Texas

PURPOSE

There is an active interest throughout the geophysical industry in magnetic recording of seismic signals. Several companies are manufacturing equipment designed for this purpose, but since these are relatively new forms of apparatus there is a lack of standardization in presentation of specifications. A purpose of this subcommittee is to propose definitions and standards applicable specifically to recording equipment designed for seismic use. No attempt will be made to define fundamentally terms such as noise, signal, etc., but such terms will be defined in context as applying to seismic equipment. This paper will present definitions and methods of measurement in tentative form which the SEG may adopt as their recommended method for specifying data pertinent to magnetic recorders. No manufacturer will be required to follow these recommendations but they will be distributed to members of the SEG. If members desire, they may request manufacturers to supply them with information in accordance with this document.

A second purpose of this subcommittee is to suggest measurement and reporting procedures which will provide data in such form so as to facilitate accurate evaluation of magnetic equipment for a particular application. If a customer can obtain data from all manufacturers according to a uniform standard, he may then have a basis for comparison.

PLAN OF WORK

The work involved in the study of the problem of establishing definitions and measurement procedures for the standardization of magnetic recording of seismic signals was performed in the following manner. Existing standards relative to this subject were studied, specific problems were analyzed by the subcommittee and assistance was obtained from men in industry having knowledge and experience in magnetic recording of seismic data. It is appropriate to acknowledge the thoughtful comments and information received from Dr. S. J. Begun, Clevite-Brush Development Company; Mr. John Jipp, Ampex Corporation; Dr. Sidney Kaufman, Shell Oil Company; Mr. A. J. W. Novak, Technical Instrument Company; Dr. A. L. Parrack, The Texas Company; Mr. R. A. Peterson, United Geophysical Company; Mr. C. B. Scott, Carter Oil Company; Mr. Walter Selsted, Ampex Corporation; Mr. R. R. Thompson, Humble Oil and Refining Company; J. D. Skelton, Carter Oil Company; J. E. Hawkins, Seismograph Service Corporation; R. A. Broding, Century Electronics and Instruments, Inc.;

J. A. Smith, Humble Oil and Refining Company; F. J. Feagan, Humble Oil and Refining Company; E. L. Koller, Ampex Corporation; A. E. Tilley, California Research Corporation; and Garry Muffly, Society of Exploration Geophysicists.

REFERENCES

To establish a reference for classification and to reduce confusion in terminology, source material was taken from the following publications:

"Acoustical terminology," Z24. 1–1951 approved by The American Standard Association, July 31, 1951, sponsored by The Acoustical Society of America in cooperation with The Institute of Radio Engineers, Inc. Obtainable from The American Standards Association, Inc., 70 E. 45th Street, New York 17, New York. Price $1.50.

Standards on sound recording and reproducing: methods of measurement of noise, 1953. This publication may be obtained from The Institute of Radio Engineers, 1 East 79th Street, New York 21, New York. It is described as 53 I.R.E. 19S1 and is also published in the Proc. IRE, volume 41, No. 4, April, 1953. Price $.50.

Standards on sound recording and reproducing; methods for determining flutter content, 1953, This publication may be obtained from The Institute of Radio Engineers, 1 East 79th Street, New York 21, New York. It is described as 53 I.R.E. 19S2. Price $.75.

Proposed standards for the measurement of distortion in sound recording. Journal of The Society of Motion Picture Engineers, volume 51, No. 5, November 1948.

"Proposed standard on audio systems and components methods of measurement: gain, amplification, loss, attenuation, frequency response," 55 IRE 3.PS1, January 20, 1955.

"Amplifiers for sound equipment," R.M.A. Standard SE-101-A (July 1949) U.S.A.

STANDARD METHODS OF SPECIFYING PERFORMANCE

Users of recording equipment may require manufacturers to provide performance information obtained by the procedures set forth in this section. Manufacturers should state specifically the apparatus under test. This would include the magnetic recording apparatus proper and such associated electronic equipment used in the tests. The manufacturer should also specify input and output test points, so that the user may be informed of the specific equipment to which the test results apply.

The following test procedures are divided into two categories:

(1) Measurements
(2) Proposed methods of measurement

Those set forth under "measurement" are procedures which can be performed with standard equipment that is generally on hand. Those tests set forth under "proposed method of measurement" will require special test equipment that may not be immediately available to the manufacturer.

Absolute timing accuracy

Definition

"Absolute timing accuracy" expresses the preciseness with which a recorder can reproduce timing of signals with respect to a time reference.

Measurement

Each manufacturer of apparatus intended for seismic use should supply a standard recording which when reproduced on the manufacturer's equipment will produce a 100 cps sinusoidal signal on all channels.

The accuracy of the wave length of the recorded signal on the recording media should be specified. This signal, when reproduced on any of the manufacturer's equipment (to which his timing claims apply), and compared with a standard 100 cps reference signal, should be within the manufacturer's timing accuracy claim at any point on the record.

If the machine to be tested has movable heads, a test should be made by changing the position of these heads by fixed time increments. A record may then be made from the standard 100 cps recording and actual time displacement checked against dial calibrations. If the manufacturer makes a claim as to the accuracy of his moving head mechanisms this should be borne out by his standard recording.

The standard reference media itself should have a stable backing. If the manufacturer believes it is significant, he may specify that the reference recording was made at a certain temperature and humidity. He may provide a correction chart for other temperatures and humidities. The user can then correct his measurements for temperature and humidity effects.

Relative timing accuracy

Definition

Relative timing errors between channels are divided into two categories.

(1) Timing errors caused by a lack of phasing between various channels of electronic equipment.

(2) Timing errors that result from the position of the recording heads with respect to the recording media being different in the recording and playback processes.

Measurement

Record a 100 cps signal on all channels of a recorder from a reference source. Make an oscillographic record and compare timing of signal traces between channels. The relative timing error is expressed by the maximum time difference between channels, in milliseconds. Repeat at 50 and 20 cps.

This measurement may be made by using an oscilloscope to compare the relative phase between the outputs of the various channels.

Transfer relative timing accuracy

Definition

The relative timing accuracy between channels when a recording is made on one machine and played back on another.

Measurement

Use the procedure set forth in the above section with the exception that the recording is to be made on one machine and played back on another.

Crossfeed

Definition

"Crossfeed" is the reproduction in one channel of a signal which has been recorded on another or other channels.

Measurement

A signal at maximum recording level should be recorded on all channels except one. Bias or carrier (with no signal) should be applied to this unrecorded channel during the recording cycle. The playback voltage from the recorded channels should be measured and compared with the crossfeed voltage played back from the channel on which no signal was placed.

The ratio between the reproduced signal and crossfeed signal will be defined as a "crossfeed ratio," and will be expressed in db. Crossfeed will be measured at 10, 20, 50 and 100 cps. The resulting data will be plotted on semilog paper. If no crossfeed can be detected at any of these frequencies, the statement will be made that crossfeed is below noise level in the recording system.

NOTE: (1) In this measurement it is assumed that the magnetic tracks are normally placed on the recording media in phase. If the recorder is not so arranged, it should be connected so as to accomplish this before the test is made.

(2) Seismic recorders are generally multi-channel devices and several arrangements of recording heads are in use. Some of these heads are arranged in line across a recording medium while others are staggered in various configurations. While it is generally accepted that the only significant crossfeed is from adjacent recording channels, various difficulties arise in defining which channels are adjacent when staggered head configurations are used. For this reason crossfeed will be measured as outlined above and the maximum crossfeed encountered should be specified.

Flutter

Definition

In recording and reproducing, flutter is the deviation in reproduced signals from their original frequencies, which generally result from irregular motion during recording, duplication or reproduction.

Proposed method of measurement

Record a 200 cps signal at maximum recording level. Play this signal back through a flutter meter consisting of an FM demodulator and a low pass filter having a cut-off of 100 cps with a maximum rejection of 200 cps. Record the result on a recording oscillograph. Flutter will be expressed as the maximum percentage of deviation from the 200 cps signal carrier observed on this oscillographic record.

NOTE: Using the test system shown below, calibration is effected by feeding the oscillator output to the flutter meter first at 200 cps and then at some other frequency. If 210 cps is used, 5 percent deviation will then be indicated on the oscillographic record.

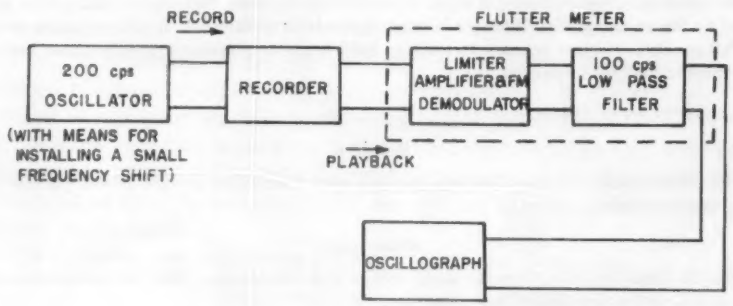


FIG. 1

Frequency Response

Definition

Frequency response is the variation in amplification as a function of frequency over the specified operating range of the recorder preferably expressed in db relative to the response at 50 cps (or any other reference frequency the manufacturer may select).

Measurement

An accurate frequency response curve is recommended. Data should be taken at as many frequencies as is necessary to guarantee the desired accuracy and should at least include measurements at those of the following frequencies which fall within the specified operating range of the recorder: 5, 10, 20, 50, 100 and 200 cps.

Time Delay

Definition

Time delay is an expression of the time differences created in a recorder between a transient signal such as a step function and various sinusoidal frequencies.

NOTE: This information is useful in seismic recording to identify errors which may be generated in the recorder between the time break and other components of the seismic signal.

Measurement

An accurate time delay vs. frequency curve is recommended. Data should be taken at as many frequencies as is necessary to guarantee the desired accuracy and should at least include measurements at those of the following frequencies which fall within the specified operating range of the recorder: 5, 10, 20, 50, 100 and 200 cps.

The time delay vs. frequency curve may be obtained by recording each of the above frequencies together with a single step function of approximately the same amplitude. A typical circuit is shown below:

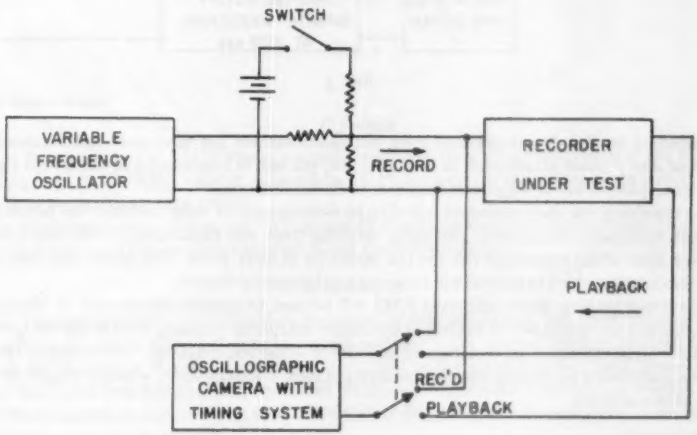


FIG. 2

An oscillographic record is made simultaneously with the magnetic recording. A second oscillographic record is made during the playback of this recording. The two oscillographic records are then compared to determine the amount of time delay at the frequency recorded. This process is repeated at each frequency where a measurement is desired.

Intermodulation

Definition

Intermodulation is the modulation of the components of a complex wave by each other, in a non-linear system.

Proposed method of measurement

Intermodulation will be measured by simultaneously recording a 20 cps signal at 80 per cent maximum recording level and a 200 cps signal at 10 per cent maximum recording level. These signals will then be played back through a band pass filter having a cut-off at 150 cps which attenuates the 20

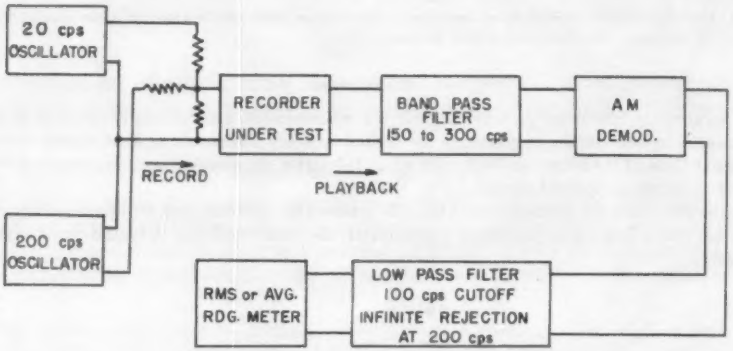


FIG. 3

cps component 60 db below reproduced level, but passes the 200 cps component unattenuated. This filter must also provide attenuation at 2nd, 3rd, 4th, 5th and 6th harmonics of the 20 cps signal so that their amplitude will be no greater than that of the fundamental.

The remaining 200 cps component will then be demodulated in order to detect the percentage of amplitude modulation it contains. The signal resulting from this demodulation will then be passed through a filter which attenuates the 200 cps carrier by at least 40 db. This leaves only the low frequency modulation which in general will be 20 cps and harmonics thereof.

An average reading meter calibrated RMS will be used to measure the amount of the demodulated signal and this meter will be calibrated in terms of maximum recording level of the 200 cps signal. The result will be expressed in percentage of modulation of the 200 cps signal. Calibration of the meter may be accomplished by feeding into the measuring system a 200 cps signal which is amplitude modulated a known amount.

Modulation noise

Definition

Noise which exists only in the presence of a signal and is a function of the instantaneous amplitude of the recorded signal. (The signal is not to be included as part of the noise.)

Proposed method of measurement

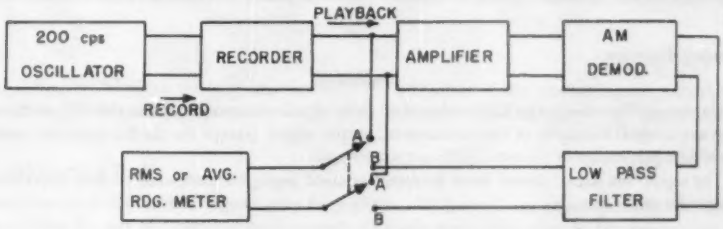
Record a 200 cps signal at maximum recording level. Play the recording back through an AM demodulator. Feed output of the AM demodulator through a low pass filter with a 100 cps cut-off frequency and a maximum rejection point at 200 cps. Read the output of the filter on an average read-

ing meter. Calibrate the system by feeding into it a 200 cps tone containing a known percentage of amplitude modulation at 40 cps. Set the gain of the amplifier in the test set up so that the following relationship is correct:

Let A be the level of the 200 cps tone as reproduced from the recorder.

Let B equal the output from the lowpass filter.

The relationship $B=(A)$ (percent mod)/100 will then be made true by setting the gain of the amplifier. Modulation noise will then be equal to: 20 log (A/B) in db.



$$B = \frac{A \times \%\ \text{MOD}}{100}$$

$$\text{MOD NOISE} = 20 \log \frac{A}{B}$$

FIG. 4

Signal-to-noise ratio

Definition

The ratio between the RMS value of a signal reproduced from a recording made at the maximum recording level, to the RMS value of noise generated by the recorder in the absence of a recorded signal in the spectrum from 20 to 200 cps.

By "absence of a recorded signal," it is meant that noise be measured on a recorder channel with the input shorted and bias or carrier applied during the recording cycle.

Measurement

(1) The signal-to-noise ratio should be measured by first recording a test signal at maximum recording level. The ratio of the test signal playback voltage, to the value of noise reproduced from the machine in the absence of a signal, expressed in db, will be the signal-to-noise ratio. Measurements may be made on a true RMS reading voltmeter. In the event this is not available, an average reading voltmeter calibrated in RMS may be used. Note that in this procedure the test signal is recorded and played back on the same machine.

(2) A noise oscillogram, made from a recording of noise at sufficient amplitude to allow its character to be observed, should also be provided. At some point during this recording a sinusoidal signal will also be recorded at a level approximately ten times the value of the noise. This sinusoidal signal will be used for the purpose of calibrating the noise record. The percentage of maximum recording level represented by the calibrating sine wave signal, should be written on the face of the oscillographic record. Timing lines should also appear on these records and the cut-off frequency of the galvanometers used should also be specified. The galvanometer frequency response should be at least 200 cps. The band width of the oscillographic recording system must be specified and this band width should at least cover the specified operating range of the recorder.

Transfer noise

Definition

Transfer noise is the noise which may be due to a magnetic recording being made on one recording apparatus and reproduced on another.

Measurement

Measurement of transfer noise will be accomplished by the method in the above section with the exception that the test signal should be recorded on one machine and transferred to another for playback.

Harmonic distortion

Definition

Harmonic distortion is the RMS value of all those signal voltages present at the output terminals which are integral multiples of the fundamental output signal (except for the fundamental itself) expressed as a percentage of the total RMS output voltage.

The input test signal should have harmonic content negligible compared to that introduced by the recorder under test.

Measurement

The total RMS harmonic distortion will be ascertained by measuring the value of each harmonic component of a recorded fundamental and computing the total RMS value of all of the measurements. The harmonic components will be measured with a wave analyzer. Distortion will be measured at 20, 50, and 100 cps. If the distortion is predominately 2nd and 3rd harmonic it should be so stated.

Distortion measured at these frequencies will show the effect of increasing level on the total value of distortion. This will be accomplished by making measurements at recording levels from 20 percent of maximum recording level, to 150 percent of maximum recording level. A curve will be drawn showing the increase of distortion with level, and as many intermediate points will be taken as required to satisfactorily define the curve.

The over-all measurement of harmonic distortion will then be presented as a family of three curves, at the three specified frequencies and showing the variation against level.

NOTE: (a) The test engineer will be depended upon to select an adequate wave analyzer, since several satisfactory commercial instruments are available.

(b) A wave analyzer having too great a selectivity could produce an error in measurement of distortion if an appreciable amount of flutter exists in the recorder.

DEFINITIONS

The following additional definitions of terms used in this report were adopted from references set forth above:

Magnetic recorder

A magnetic recorder is equipment incorporating an electromagnetic transducer and means for moving a ferromagnetic recording medium relative to the transducer for recording electric signals as magnetic variations in the medium.

NOTE: The generic term "magnetic recorder" can also be applied to an instrument which has not only facilities for recording electric signals as magnetic variations, but also for converting such magnetic variations back into electric variations.

Magnetic recording medium

A magnetic recording medium is a magnetizable material used in a magnetic recorder for retaining magnetic variations imparted to it during a recording process. It may have the form of a wire, tape, cylinder, disc, etc.

Magnetic recording reproducer

A magnetic recording reproducer is equipment for converting magnetic variations on magnetic recording media into electric variations.

Maximum recording level

The maximum recording level is the maximum level at which the recorder was designed to normally operate. It is also the level used during the measurement of maximum harmonic distortion. Recordings made at higher values of recording level may result in increased amounts of harmonic distortion.

Noise

Any output signal which tends to interfere with the utilization of the applied signals, except for output signals which consist of harmonics and subharmonics of input signals and intermodulation products.

Recomended recording level

It is recognized that seismic signals may have peaks which stand out above the average signal level, even with the use of automatic level control. For this reason the manufacturer may wish to recommend a recording level for the average signal which is lower than the maximum recording level.

The recommended recording level will be expressed as a percentage of the maximum recording level.

L. W. ERATH

DEPARTMENTS

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,784,370. B. Morrison. Iss. 3/5/57. App. 12/19/52. Assign. Hudson Bay Mining and Smelting Co. Ltd.

Geophysical Prospecting. A method of electrical prospecting using electrodes above the ground and measuring the local terrestrial electric field or adjusting the heights of spaced electrodes until their potentials are the same and recording the heights.

U. S. No. 2,790,137. F. M. Mayes. Iss. 4/23/57. App. 6/12/53. Assign. Sun Oil Co.

Electrical Prospecting Method and Apparatus. An electrical prospecting system using two current electrodes and two pairs of potential electrodes symmetrically located with respect to a center point of the current electrodes and measuring the algebraic sum of the potentials so that interfering potentials are cancelled out.

GEOCHEMICAL PROSPECTING

U. S. No. 2,786,144. P. B. Weisz. Iss. 3/19/57. App. 12/12/51. Assign. Socony Mobil Oil Co., Inc.

Method for Detecting Hydrocarbons in Soil Gases. A method of detecting minute amounts of hydrocarbon in soil gas by mixing the soil gas with argon and passing an ionizing discharge through the mixture and subsequently detecting the presence of hydrocarbon ions by means of a g-m counter in the same tube.

GRAVIMETRIC PROSPECTING

U. S. No. 2,787,417. J. W. Northrup and G. A. Schurman. Iss. 4/2/57. App. 7/30/53. Assign. California Research Corp.

Geological Anomaly Gravity Analog Computor. An analog computer for the vertical gravity due to a known anomaly in which the mass configuration is simulated by an array of lights and a photographic plate is placed at a distance corresponding to that of the plane of observation, changes in the mass configuration with depth being simulated by moving the photographic plate to different distances and reexposing so that the final darkening of the plate is proportional to the summation.

MAGNETIC PROSPECTING

U. S. No. 2,785,376. A. Hazeltine. Iss. 3/12/57. App. 3/4/55. Assign. Hazeltine Research, Inc.

Apparatus for Utilizing the Earth's Magnetic Field to Indicate Aircraft Velocity. A device having a dipole rotated on an axis perpendicular to the magnetic field and parallel to the direction of translation, the conductors being connected through slip rings to an impedance and the a-c voltage across the impedance measured.

U. S. No. 2,786,179. D. C. Arnold and P. A. McKinley. Iss. 3/19/57. App. 6/29/53. Assign. Collins Radio Co.

Flux Detector. A magnetic detector having an annular shield wound with a coil excited by a-c and

* Gulf Oil Corporation, Patent Department.

pick-up coils inside the shield to pick up the external flux that penetrates the shield when saturated at the a-c peaks.

U. S. No. 2,792,782. R. J. Schiller. Iss. 5/21/57. App. 3/30/50.

Magnetic Field Sensitive Apparatus. A magnetic detector having a linear array of bar magnets with adjacent slightly spaced poles of opposite polarity and a magnetic needle suspended in the area of zero field which lies to one side of the gap, the proximity of extraneous magnetic field causing distortion of the field and movement of the needle.

RADIOACTIVITY PROSPECTING

U. S. No. 2,789,242. H. Friedman and M. McKeown. Iss. 4/16/57. App. 2/13/46.

Geiger-Mueller Counter. A temperature-compensated radiation counter having a Geiger-Mueller tube with a heating coil around the cathode cylinder and the entire tube surrounded by an evacuated envelope.

U. S. No. 2,793,309. J. A. Simpson, Jr. Iss. 5/21/57. App. 10/31/46. Assign. U.S.A.

Neutron Proportional Counter. A proportional counter for neutron absorption measurements having a block of methyl methacrylate with an orifice with central wires and conducting plates one of which has a coating of material emitting ionizing radiation upon neutron absorption.

SEISMIC PROSPECTING

U. S. No. 2,784,942. R. V. Peck and J. N. Stoddard. Iss. 3/12/57. App. 1/11/55. Assign. California Research Corp.

Apparatus for Simultaneously Drilling and Casing Shot Holes. A shot-hole drill using a drill bit with a collapsible underreamer and having a hole in the rotary table large enough to insert the casing after which slips are inserted to engage the kelly, the casing top being below the rotary table and connected to the bottom of the kelly to apply weight so that the casing follows the drill into the hole.

U. S. No. 2,785,356. R. G. Nisle. Iss. 3/12/57. App. 6/13/55. Assign. Phillips Petroleum Co.

Transducer. An electromagnetic transducer having a coil in an air gap at each end of an annular magnetic circuit with a central core, the core being excited by a-c and the signal coils connected to feed-back coils on the core so that the system acts as a magnetic amplifier for the generated signal.

U. S. No. 2,786,987. R. N. Jolly. Iss. 3/26/57. App. 8/3/54. Assign. Esso Research and Engineering Co.

Lock-In Geophone for Boreholes. A device for holding a small deep-well geophone in contact with the borehole wall and also eliminating cable noise by mounting the geophone on one of three bow springs whose ends are fastened to collars through which a weighted rod passes, with coil springs between the collars and weights on the rod.

U. S. No. 2,788,510. E. T. Howes. Iss. 4/9/57. App. 7/6/53. Assign. United Geophysical Corp.

Seismic Prospecting Apparatus. A cable-coupling for a well seismometer having coaxial tubular end members connected by a helical spring covered by a rubber sleeve with the connecting wires passing through the center with slack, two such units being used with a mass between them to isolate the seismometer from cable-borne vibrations.

U. S. No. 2,788,511. E. H. Marshall. Iss. 4/9/57. App. 8/24/53. Assign. Texas Instruments Inc.

Lightweight Seismometer. An electrodynamic seismometer whose coil is suspended in an annular air gap by two flat two-arm spiral springs at the top and one at the bottom end of a rod passing through the central part of the magnet, one of the two upper springs being rotated 90° to increase transverse rigidity of the suspension system.

U. S. No. 2,788,512. W. J. Reichert. Iss. 4/9/57. App. 6/12/53 and 6/9/54. Assign Shell Development Co.

Low Frequency Seismometer. An electrodynamic seismometer whose coil is suspended in an annular air gap by an axial rod on cantilever springs and having tension springs at an upward angle to the coil axis to compensate for sag and also having opposing compression springs acting transversely on the rod to increase the period of the suspended system.

U. S. No. 2,788,513. E. T. Howes. Iss. 4/9/57. App. 6/14/54. Assign. United Geophysical Corp.

Cable. Hydrophone and cable assembly for vertical velocity shooting having a central strain element and twisted pairs of vinyl insulated conductors coated with graphite to provide shielding, the respective conductors being drawn out of the protective vinyl sheath and connected to radially-polarized semi-cylindrical piezoelectric crystal units covered by a vinyl casing.

U. S. No. 2,789,192. G. E. White. Iss. 4/16/57. App. 7/15/50. Assign. Statham Laboratories, Inc.

Vibrometers. A vibrometer having two liquid-filled chambers with yieldable walls connected by a conduit of length greater than the separation of the chambers and an electric strain gauge mechanically connected to the yieldable wall of one of the chambers.

U. S. No. 2,790,964. G. A. Schurman. Iss. 4/30/57. App. 3/2/54. Assign. California Research Corp.

Logging Tool. A deep well seismometer in which the cable is fastened to a heavy perforated protective case carrying a flexible oil-filled membrane surrounding a moving-coil seismometer, so that cable noise acts on a heavy mass but the formation energy acts through the oil on a light mass to increase the formation break as compared with the cable break.

U. S. No. 2,791,288. E. H. Maier. Iss. 5/7/57. App. 1/18/52. Assign. 10% to Seymour M. Rosenberg.

Methods and Apparatus for Presenting Seismic Information. A seismic presentation system in which the geophone signal is differentiated, amplified, converted to square waves and recorded by means of a biased glow tube to produce a duodensity record.

U. S. No. 2,791,751. S. Fine and R. E. Scott. Iss. 5/7/57. App. 11/23/53. Assign. U.S.A.

Non-Linear Time Domain Filters. A filter system for separating a sinusoidal wave and a higher amplitude non-sinusoidal wave by differentiating the combined signal to shift the phase of the sinusoidal wave and convert the non-sinusoidal wave to a series of narrow pulses of high amplitude separated by relatively long time intervals, clipping to remove the narrow pulses, integrating to recover the sinusoidal signal and combining with the original signal to recover the non-sinusoidal component.

U. S. No. 2,791,757. F. G. Blake, G. A. Schurman, and P. M. Aagaard. Iss. 5/7/57. App. 3/24/54. Assign. California Research Corp.

Pressure Cable Construction. A seismometer streamer for marine operations having a series of cylindrical piezoelectric pressure detectors embedded in the sheath and a flexible helical strengthening member with an internal resilient tube into which liquid may be introduced under pressure to control buoyancy of the streamer.

U. S. No. 2,792,067. R. A. Peterson. Iss. 5/14/57. App. 11/12/52. Assign. United Geophysical Corp.

Geophysical Prospecting System. A seismic prospecting system in which geophones are vertically spaced beneath the weathered layer and records are made of shots at successively distant shot points along a profile line.

U. S. No. 2,792,068. R. A. Peterson. Iss. 5/14/54. App. 5/6/53. Assign. United Geophysical Corp.

Geophysical Prospecting System. A seismic prospecting system in which geophones are spaced hori-

zontally along the profile line and other geophones are spaced vertically in a hole on the line, the shot points also being on the profile line, and all geophone traces are recorded on a common record.

U. S. No. 2,792,562. B. M. Baker. Iss. 5/14/57. App. 7/20/54. Assign. Texas Instruments Inc.

Horizontal Seismometer. A seismometer in a cylindrical case with two parallel bar magnets of unequal weight extending from a ball bearing on the axis of the case and a coil mounted on a cantilever rod on the axis of the case so that the coil is opposite the outer ends of the magnets which are of opposite polarity.

U. S. No. 2,793,355. C. O. Randall, L. D. Zepernick, and K. W. McLoad. Iss. 5/21/57. App. 2/11/54. Assign. Vector Mfg. Co.

Geophone Clip. A clip for attaching a geophone to a cable take-out, the clip having spring-actuated plastic jaws with metal inserts to contact the two cable electrodes.

U. S. No. 2,793,833. J. P. Daniel, Sr. Iss. 5/28/57. App. 2/19/53.

Method for Charging Shot Holes. A system for loading seismic shot holes in unconsolidated formations by drilling with a bit having a plug in its lower end, lowering the charge through the drill string and knocking out the plug, and retrieving the drill bit and drill string.

U. S. No. 2,794,177. J. F. Johnson. Iss. 5/28/57. App. 7/28/53. Assign. Sinclair Oil & Gas Co.

Prospecting System. A seismograph volume control system in which the vertical component and the horizontal component of the seismic waves are separately detected and amplified, and the horizontal component signal used to reduce the gain of the vertical component amplifier whose output is recorded.

WELL LOGGING

U. S. No. 2,783,646. R. C. Rumble. Iss. 3/5/57. App. 12/9/54. Assign. Esso Research and Engineering Co.

Flowmeter for Wells. A flowmeter for measuring downward flow in a well having an annular upwardly-tapered flow tube with an annular magnetic rotameter float connected by a rod to a buoyant float in a chamber of liquid, and a central tube with a magnetic follower connected to a recording pen.

U. S. No. 2,784,796. W. C. Overton, Jr. Iss. 3/12/57. App. 1/25/52. Assign. Socony Mobil Oil Co., Inc.

Shear Modulus Acoustic Well Logging. An acoustic logging system in which a low frequency sound wave is generated in the borehole fluid and reflected from a spaced reflector in the bore-hole fluid and the standing wave system observed with transducers between them, the wave having a wave length greater than the circumference of the well bore so that its velocity is affected by the shear modulus of the formation wall.

U. S. No. 2,785,314. J. H. Grahame. Iss. 3/12/57. App. 9/28/51. Assign. The Texas Co.

Radioactivity Earth Exploration. A radioactivity logging system whose sonde has a source of neutrons and two scintillation detectors on the same horizontal plane vertically spaced from the source, one detector being appropriately shielded so that it detects only induced gamma rays and the other unshielded so that it detects all radiation, and recording the difference between detector signals as well as the signal from the shielded detector.

U. S. No. 2,785,315. C. Goodman. Iss. 3/12/57. App. 3/11/52. Assign. Schlumberger Well Surveying Corp.

Nuclear Well Logging. A porosity logging system in which a gamma-ray source emitting photons whose energy is slightly in excess of 2.23 mev is placed in the formation by means of a bullet or side-

wall core barrel far enough so that the gamma rays do not reach the borehole, and detecting in the borehole neutrons produced by photodisintegration of hydrogeneous (deuterium) material in the formation pores.

U S. No. 2,785 374. C. H. Fay and R. P. Gilmore. Iss. 3/12/57. App. 6/16/53. Assign. Shell Development Co.

System for Analyzing the Composition of Fluid Mixtures. A system for determining the composition of fluids in a borehole having a sonde in which the fluid forms the dielectric of a condenser connected to a variable-frequency oscillator and also having a fixed-frequency oscillator, the beat frequency being conducted to the surface and recorded with a frequency meter.

U. S. No. 2,786,178. H. G. Doll. Iss. 3/19/57. App. 12/19/51. Assign. Schlumberger Well Surveying Corp.

Apparatus for Electrical Well Logging. A device for measuring electrical resistivity of formations in different directions having a pad of insulating material pressed against the borehole wall by a spring, the face of the pad against the formation carrying a current electrode and potential electrodes in different azimuths.

U. S. No. 2,786,351. B. F. Wiley and R. A. Doubt. Iss. 3/26/57. App. 8/9/54. Assign. Phillips Petroleum Co.

Flowmeter. A well flowmeter having an impeller which rotates upwardly-extending fingers of magnetic material outside of a nonmagnetic housing with a bar magnet whose ends have radially-extending arms, the magnet being wound with a coil whose induced pulses are counted at the surface.

U. S. No. 2,787,757. R. G. Piety. Iss. 4/2/57. App. 12/22/52. Assign. Phillips Petroleum Co.

Method and Apparatus for Logging Wells. An electric logging system using a long cylindrical current electrode centered in the well bore and surrounded by a coaxial second lattice-like electrode in the shape of a truncated ellipsoid, and a third electrode in the contour of the second electrode, the current to a distant electrode and the potential differences of the electrodes being measured.

U. S. No. 2,787,758. J. E. Walstrom. Iss. 4/2/57. App. 3/13/50 and 6/8/53. Assign. California Research Corp.

Apparatus for Electrical Well-Logging. A self-potential internal-resistance logging apparatus having electrodes connected to two or more potential-measuring circuits of different impedance whose logs are recorded on the same depth chart.

U. S. No. 2,787,759. J. J. Arps. Iss. 4/2/57. App. 8/31/50.

Apparatus for Logging Wells. A system for electric logging while drilling having a turbine-driven generator in the drill stem connected to two electrodes in series with a motor which drives an a-c generator at a frequency related to the electrode current, the a-c generator actuating a high-speed valve to generate in the drilling fluid an acoustic wave which is detected at the surface and its frequency indicated.

U. S. No. 2,787,839. E. E. Taylor. Iss. 4/9/57. App. 5/11/51.

Combination Pivotal Electrode Vacuum Tube and Magnetic Actuating Devices. A transducer for a well-surveying apparatus, weight indicator, caliper, pressure gauge, etc. in which the moving element has a magnet which moves a follower inside a vacuum tube to vary the effective electron flow area, the tube being connected in a circuit with an indicator.

U. S. No. 2,787,906. R. G. Piety. Iss. 4/9/57. App. 6/30/52. Assign. Phillips Petroleum Co.

Apparatus for Determining Temperature Conditions in a Well. A thermal logging apparatus and

well flowmeter having two pairs of spaced resistance coils in opposite arms of a bridge circuit for measuring temperature gradient and an electric heating coil which heats the well fluid for the detection of leaks by anomalous gradients.

U. S. No. 2,788,662. B. F. Wiley. Iss. 4/16/57. App. 12/29/52. Assign. Phillips Petroleum Co.

Improved Apparatus for Making Measurements in a Well. A differential temperature logging device having spaced resistance coils connected into opposite arms of a bridge circuit, each pair of coils being wound on a thin metallic spool and covered by a thin metallic sleeve and mounted concentrically on the cable so as to permit free circulation of fluid inside and outside each thermometric unit.

U. S. No. 2,790,138. A. Pouporr. Iss. 4/23/57. App. 8/9/55. Assign. Schlumberger Well Surveying Corp.

Induction Well Logging. An induction logging system using two energizing coils excited at two different frequencies and two symmetrically-located pick-up coils, the areas of the coils and intensity of excitation being related to the frequency in specified manner, and detecting the conductive signal in each pick-up coil by means of phase-sensitive discriminators whose outputs are combined.

U. S. No. 2,791,035. E. B. Roxstrom. Iss. 5/7/57. App. 10/27/53. Assign. Svenska Diamantbergborrnings Aktiebolaget.

Device for Determining the Inclination and Direction of Drill Holes in the Ground. An inclinometer having an electromagnet connected to a battery and ammeter at the surface and a permanent magnet pivoted on a transverse axis close to the electromagnet with a pendulous contact arm, the electromagnet current being calibrated and adjusted to just open the contact.

U. S. No. 2,791,907. G. M. Griner and C. J. Crane. Iss. 5/14/57. App. 5/19/54. Assign. Gladys M. Griner.

Device for Indicating Stages of Fluid Depth of Water in Wells. A fluid level indicator having a spring-supported wire line carrying vertically-spaced sinkers, the change in weight of the system under submersion being indicated by a pointer connected to the spring.

U S. No. 2,792,637. H. O. Seigel and W. E. Bell. Iss. 5/21/57. App. 1/15/52. Assign. Newmont Mining Corp.

Apparatus for Surveying Drill Holes. An inclinometer and curvature detector having a tubular case capable of lateral bending with a marked weighted disc pivoted about the longitudinal axis of the case and an axial light beam that photographically registers the orientation of the disc and whose deviation from the axis measures the curvature.

U. S. No. 2,794,182. H. M. Buck. Iss. 5/28/57. App. 8/8/55. Assign. Esso Research and Engineering Co.

Flow Indicating Device. A well flow indicator in which the flow causes a clapper to strike the instrument frame and the sound is picked up by a microphone connected to the surface.

See also Patents 2,786,987; 2,788,510; 2,790,964 listed under Seismic Prospecting; and 2,786,661; 2,792,708; 2,793,187 listed under Miscellaneous.

MISCELLANEOUS

U. S. No. 2,784,786. J. E. Walstrom. Iss. 3/12/57. App. 6/26/53. Assign. California Research Corp.

Formation Testing Apparatus. A drill-pipe device for sampling formation fluid having a toggle that is released by setting the device on bottom and which holds the device against the borehole wall, and having a cavity charge that perforates the device and the formation so that formation fluid can enter a sample chamber which is closed by rotation of the drill pipe.

U. S. No. 2,786,629. R. G. Piety. Iss. 3/26/57. App. 3/16/51. Assign. Phillips Petroleum Co.

Electrical Computer. An analog computer for solving vapor-liquid equilibrium problems in which the mol fractions of the components are set on dials of potentiometers with a common voltage source and the equilibrium constants are represented by resistors connected through other ganged resistors from the contactor to the end of the potentiometers, the potential across the equilibrium-constant resistors being doubled by means of amplifiers whose outputs are summed and fed to a voltage divider which is adjusted to balance the source voltage.

U. S. No. 2,786,661. G. Herzog and R. B. Stelzer. Iss. 3/26/57. App. 3/30/53. Assign. The Texas Co.

Method for Forming and Surveying a Cavern in a Salt Formation. An electrical method of determining the diameter of a salt cavity filled with brine of known resistivity by placing a pair of close vertically-spaced potential electrodes at the location and passing a known current vertically through the brine by means of other electrodes and measuring the current and potential.

U. S. No. 2,786,977. L. Blagg and L. H. Robinson, Jr. Iss. 3/26/57. App. 10/19/55. Assign. Esso Research and Engineering Co.

Filtration and Electrical Resistivity Measuring Device. Apparatus for measuring the electrical resistivity of drilling mud, mud filtrate and mud cake having a cylindrical container with a filter at the bottom through which filtrate is forced by a plunger, electrodes being provided on the bottom of the container and the bottom of the plunger and in a collecting chamber for the filtrate.

U. S. No. 2,790,186. L. T. Carapellotti. Iss. 4/30/57. App. 9/30/53. Assign. U.S.A.

Sonobuoy Stabilizer. A sonobuoy having an upper sealed radiotransmitting compartment and a lower compartment which houses the hydrophone when not in use and from which the hydrophone may be suspended in use, the lower compartment also having small openings at the top to admit water.

U. S. No. 2,791,257. E. W. Jacobson and B. M. Wedner. Iss. 5/7/57. App. 3/22/54. Assign. Gulf Research & Development Co.

Traction Link for Marsh Buggy Wheels. A traction device having a flexible cable fastened crosswise of a vehicle tire and on which are threaded a number of rubber segments of multi-angular cross section.

U. S. No. 2,791,375. R. G. Piety. Iss. 5/7/57. App. 1/2/53. Assign. Phillips Petroleum Co.

Simulator. A mechanical analog of a pumping well using three tensioned cords with weights located along their length, the weights representing respectively sucker-rod segments, oil-column segments, and tubing segments, with viscous coupling between corresponding weights of two pairs of cords and a mechanical oscillator to impart transverse oscillations to the sucker-rod cord.

U. S. No. 2,792,072. P. J. Moore. Iss. 5/14/57. App. 10/14/53. Assign. National Lead Co.

Gas Extracting Apparatus. A device for extracting and collecting gas from drilling mud in the mud ditch having a cylindrical case with an opening in the bottom and on the side and a motor driven impeller which stirs the mud, admixes air and effects circulation through the openings, the gas and air released being drawn off at the top of the cylinder.

U. S. No. 2,792,173. N. A. Schuster. Iss. 5/14/57. App. 8/13/53. Assign. Schlumberger Well Surveying Corp.

Function Generator. A computer for transposing a function $z=f(x, y)$ plotted as a family of curves on a continuous belt to a function $y=f(x, z)$ by photoelectrically scanning the curves and integrating the curve impulses and comparing with impulses from indicia along the axis of the dependent variable.

U. S. No. 2,792,708. R. W. Johnston, Jr. and A. M. Shook. Iss. 5/21/57. App. 11/22/52. Assign. The Texas Co.

Testing Underground Storage Cavities. A method of surveying a storage cavity full of liquid by introducing a lighter immiscible liquid and measuring the volumes and pressures of liquid displaced and fluid introduced.

U. S. No. 2,792,709. T. W. Bell and H. C. Stone. Iss. 5/21/57. App. 11/24/54. Assign. The Texas Co.

Apparatus Determining Static Pressures in Pumping Wells. A device permitting measurement of bottom-hole pressure in a pumping well with high-viscosity fluid which uses hollow sucker rods with a check valve at the lower end, gas being introduced through the rods and the bottom-hole pressure computed from the gas pressure at the surface and the gas density.

U. S. No. 2,793,187. P. W. Fischer. Iss. 5/21/57. App. 12/21/53. Assign. Union Oil Co. of Calif.

Conductive Oil-Base Drilling Fluids. A conductive calcium-contaminated oil-base drilling mud having a conductivity additive containing sodium hydroxide, sodium silicate, trisodium pyrophosphate, sulfonated castor oil and sodium humate.

U. S. No. 2,793,320. O. L. Patterson and E. W. Yetter. Iss. 5/21/57. App. 7/30/51. Assign. Sun Oil Co.

Memory Tube Function Generator. A system in which a curve is recorded on a memory tube and read out by a c-r beam having horizontal sweep and whose direction of vertical sweep reverses each time the beam crosses the recorded curve so that the beam traces the curve by zig-zagging at high frequency.

SELECTED LIST OF U. S. PATENTS ISSUED DURING MARCH, APRIL, AND MAY OF 1957

Patent No.	*Subject**	*Patent No.*	*Subject**	*Patent No.*	*Subject**
2,783,641	412	2,784,786[a]	392	2,785,631	48
2,783,642	12	2,784,796[a]	8	2,785,633	136
2,783,643	492	2,784,904	68	2,785,853	68
2,783,645	428	2,784,905	68	2,785,854	68
2,783,646[a]	148	2,784,906	68	2,785,857	68
2,783,647	16	2,784,907	68	2,785,892	224
2,783,732	16	2,784,908	68	2,785,942	324
2,783,733	12	2,784,909	68	2,786,144[a]	172, 168
2,783,940	68, 16	2,784,910	308	2,786,178[a]	116
2,783,941	68	2,784,942[a]	360, 384	2,786,179[a]	232
2,783,942	68	2,785,038	224	2,786,193	12, 108
2,783,969	80	2,785,232	224	2,786,197	316
2,784,259	224	2,785,233	224	2,786,350	168
2,784,317	236	2,785,314[a]	304	2,786,351[a]	148
2,784,318	236	2,785,315[a]	304	2,786,354	148
2,784,325	140	2,785,356[a]	484	2,786,356	16
2,784,335	196	2,785,374[a]	116, 508	2,786,357	16
2,784,370[a]	124	2,785,376[a]	232, 16	2,786,481	288
2,784,396	68	2,785,395	316	2,786,548	324
2,784,401	16	2,785,470	428	2,786,559	324
2,784,593	288	2,785,573	16	2,786,628	68

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947.)

[a] Abstracted on preceding pages of this issue.

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2,786,629[a]	68
2,786,661[a]	116
2,786,895	224
2,786,896	224
2,786,897	224
2,786,899	484
2,786,946	236
2,786,955	484
2,786,977[a]	88
2,786,987[a]	376
2,786,993	316
2,786,994	312
2,787,158	12, 140
2,787,159	428
2,787,160	12, 200
2,787,417[a]	68, 180
2,787,418	68
2,787,511	324
2,787,512	324
2,787,513	324
2,787,514	224
2,787,678	4
2,787,685	460
2,787,714	308
2,787,757[a]	116
2,787,758[a]	116
2,787,759[a]	208
2,787,777	484
2,787,783	200
2,787,834	428
2,787,839[a]	484, 520
2,787,906[a]	452
2,787,916	40
2,788,254	324
2,788,451	236
2,788,454	484
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2,788,512[a]	376
2,788,513[a]	40, 360
2,788,516	484
2,788,654	380
2,788,662[a]	452
2,788,664	288
2,788,665	288
2,788,938	68
2,789,192[a]	376
2,789,242[a]	308
2,789,285	316
2,789,427	428
2,789,434	148
2,789,435	148
2,789,436	16
2,789,580	484
2,789,759	68
2,789,760	68
2,789,776	324
2,789,790	80
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2,791,288[a]	360, 364
2,791,375[a]	68
2,791,398	80
2,791,482	324
2,791,483	324
2,791,640	224
2,791,698	416
2,791,746	324
2,791,747	68
2,791,751[a]	348
2,791,756	108
2,791,757[a]	360, 40, 376
2,791,764	68
2,791,902	496
2,791,907[a]	508
2,792,067[a]	360
2,792,068[a]	360
2,792,072[a]	168, 252
2,792,173[a]	68
2,792,274	216
2,792,455	324
2,792,456	484
2,792,481	40
2,792,484	460
2,792,500	308
2,792,501	168
2,792,542	324
2,792,548	168
2,792,562[a]	376
2,792,566	200
2,792,570	312
2,792,637[a]	520
2,792,708[a]	520
2,792,709[a]	288
2,792,710	200
2,792,782[a]	232
2,792,783	48
2,792,804	12
2,792,902	12
2,792,988	68
2,792,992	68
2,793,039	224
2,793,187[a]	116
2,793,249	12
2,793,255	484
2,793,288	324
2,793,295	236
2,793,297	308
2,793,298	308
2,793,309[a]	308
2,793,320[a]	68
2,793,321	324
2,793,344	224
2,793,345	140
2,793,355[a]	40, 360
2,793,360	68
2,793,363	312
2,793,526	188
2,793,527	188, 396, 116
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2,793,624	148
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2,793,833[a]	360, 136
2,794,125	236
2,794,126	236
2,794,173	68
2,794,177[a]	360, 372
2,794,182[a]	144

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Bulletin d'Information de l'U.G.G.I., v. 5, n. 16 (December, 1956)
Butsuri-Tanko (Geophysical Exploration), v. 10, n. 1 (1957)
Canadian Geophysical Bulletin, v. 9 (December, 1956)
Deutsches Hydrographisches Institut Jahrbuch, v. 9 (1956)
Deutsche Hydrographische Zeitschrift, v. 9, n. 5 (1956)
Economic Geology, v. 52, nos. 2 & 3 (March–April & May, 1957)
Erdol und Kohle, v. 10, nos. 3, 4 & 5 (March, April & May, 1957)
Geifizikai Koslemenyek, v. 5, n. 4 (1956)
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Journal of Earth Sciences Nagoya University, v. 4, n. 2 (December, 1956)
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Laurium (Athens), v. 4, n. 1 (1956)
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Science Reports of the Tohoku University, v. 8, n. 2 (February, 1957)
South Australia Department of Mines, Mining Review, n. 101 (1956)
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Tellus, v. 9, nos. 1 & 2 (February & May, 1957)
Transactions American Geophysical Union, v. 38, nos. 2 & 3 (April & June, 1957)
Transactions & Proceedings of the Geological Society of South Africa, v. 59 (1956)
Zeitschrift fur Geophysik, v. 23, n. 2 (1957)

MEMORIAL

HERBERT VINSON CROWDER

HERBERT VINSON CROWDER passed away suddenly on July 19, 1956 in Billings, Montana. His untimely death from an unexpected heart attack came as a tremendous shock to his family, friends, and associates. He was affectionately known to his many friends as "Bubba." He was born in Houston, Texas on May 2, 1909. He received his engineering education at the University of Texas where he graduated in 1932. He was a member of Phi Gamma Delta fraternity.

Bubba entered the geophysical profession early in 1933 as a recording helper for Seismic Explorations, Inc. of Houston, Texas, on its first seismic party in the days when one of the chief duties of a recording helper was digging geophone holes with a hand auger. He learned the seismograph business from the ground up and advanced rapidly through the various field and office jobs with the Seismic Explorations crews. He became party chief in January 1938, and supervisor, stationed in Houston, in January 1943. He attained a respected position as an experienced and competent geophysicist among his clients and associates. He was one of the too few men in the industry who, from personal experience, knew

how to get the geophysical job done irrespective of conditions or areas from the swamps of South Louisiana to the Gulf Coastal Plains, and from West Texas to the Rocky Mountains.

He resigned from Seismic Explorations, Inc. in May, 1953 to become a partner in Nance Exploration Company and moved to Billings, Montana where he quickly established himself in his profession in the Billings community. He transferred his church affiliation from the Chapelwood Methodist Church of Houston to the First Methodist Church of Billings. He was a member of the Petroleum Club, the Yellowstone Country Club, and the Rotary Club.

He was one of the organizers and the first president of the Montana Geophysical Society.

His other professional society affiliations were the Society of Exploration Geophysicists, American Association of Petroleum Geologists (associate), Casper Geophysical Society, Canadian SEG, and Billings Geophysical Society.

He is survived by his wife, Vera Baker Crowder, who is now living in Houston, Texas; by his mother, and by one brother.

Bubba was gifted with a friendliness and frankness that, coupled with his enthusiasm and energy, attracted a wide circle of friends and professional associates. In his untimely passing at the age of 47 the geophysical industry lost one of its respected "old timers" who made many valuable contributions to the industry and to its societies. He was well loved and will long be remembered by all who were privileged to know him.

JOHN D. MARR

Houston, Texas
July 17, 1957

CONTRIBUTORS

BERCKHEMER DAVIS EISLER ERATH

HANS BERCKHEMER received his Diploma in Physics in 1951 and the Dr. rer. nat. degree in 1954 from the Institute of Technology, Stuttgart, Germany. Since 1951 he has served as a research associate at the Earthquake Research Institute, Stuttgart. In 1954 he was awarded a Fulbright Fellowship and came to the Lamont Geological Observatory, Columbia University, N. Y., doing special research. He participated in the 1954 Atlantic deep sea expedition of Columbia University and joined the Mediterranean expedition of that institute in 1956.

WILLARD E. DAVIS received the B.S. degree in ceramic engineering from Missouri School of Mines and Metallurgy in 1930. He was an engineer for the Illinois State Highway Commission from 1930 to 1933, when he joined the Missouri Geological Survey as a geological engineer. While hoding that position he completed two years of postgraduate work in geology and geophysics at his alma mater. From 1944 to 1948 he was a geophysicist with the U. S. Bureau of Mines, working on projects in the central and western United States. In 1948 he joined the U. S. Geological Survey and served as geophysicist on projects in the United States, Iceland and Cuba until February, 1957, when he became Acting Chief, Ground Surveys Section, Geophysics Branch.

Mr. Davis is a member of the American Geophysical Union.

JOSEPH D. EISLER received his B.S. in electrical engineering in 1932 from the Massachusetts Institute of Technology, and his M.S. in electrical engineering in 1954 from Oklahoma State University. He entered the field of geophysics in 1936 when he was employed by Western Geophysical Company. In 1938 he was transferred to Tulsa and became a member of the research staff of the Pan American Petroleum Corp. Research Laboratories. During the war he joined the NDRC group at The Franklin Institute in Philadelphia, engaging on a defense project dealing with aircraft-to-aircraft fire control. He then returned to Pan American Research Laboratories where he has been ever since. His work ranged from instrument development and design to fundamental seismic research. At the present time he is research section supervisor in charge of geophysical research. He is a member of the Society of Exploration Geophysicists, Geophysical Society of Tulsa, American Geophysical Union, Seismological Society of America, Institute of Radio Engineers, Sigma Xi, and EKN.

LOUIS W. ERATH is a research engineer specializing in the development of electronic apparatus. He has been associated with the Southwestern Industrial Electronics Company since the summer of 1948, and he now holds the position of vice president in charge of research and development.

During the past four years, Mr. Erath has been occupied with the application of magnetic re-

cording to seismic prospecting as well as the development of the necessary apparatus. He also designed the laboratory test apparatus which this company manufactures.

In 1947 and 1948 he was a member of the engineering staff of the Schlumberger Well Surveying Corporation where he designed electronic circuitry for the gamma-ray well logging sonde.

During the years from 1942 to 1947, he was employed by the Naval Ordnance Laboratory in Washington, D. C., where he developed a magnetometer depth charge firing mechanism. In 1945 he was made head of the electrical engineering subdivision of the VT fuse division. In this capacity he made several improvements which were incorporated in the VT fuse during the post-war period.

From 1940 to 1942 he was a member of the staff of the general engineering department of the United Gas Pipe Line Company in Shreveport, Louisiana, where he worked on the development of cathodic protection of pipelines.

He attended Louisiana State University from 1934 to 1939 where he majored in physics and electrical engineering. He holds many U. S. patents and is the author of numerous technical articles. He is a member of the Society of Exploration Geophysicists and is the past chairman of the Houston section of the Institute of Radio Engineers.

R. W. FREDRICKS was born in Honolulu, T. H., on December 4, 1927. During the period 1946–48 he served in the U. S. Army with the Manhattan District and the armed forces special weapons project at Sandia Base, N. Mex. in a technical capacity. From 1949 to 1951 he attended Santa Monica City College as a pre-physics major. During the Korean conflict Mr. Fredricks served as an active duty reservist in the U.S.A.F., and supervised an engineering drafting section. He received the B.S. degree in physics in June, 1955, and the M.S. degree in physics in January, 1957, both from the University of California at Los Angeles.

From 1952 to 1953, Mr. Fredricks was employed by the Rand Corporation. Since 1955 he has been a graduate research assistant at the Institute of Geophysics at U.C.L.A., doing research on the propagation and scattering of elastic waves. He is currently engaged in research leading to the Ph.D. degree in physics.

Mr. Fredricks was the Shell Fellow in Geophysics at U.C.L.A. during the academic year 1955–56. He is a member of Sigma Pi Sigma, an associate member of Sigma Xi, and a student member of the Institute of Radio Engineers.

ANTHONY GANGI was born in Newark, New Jersey on February 19, 1929. He received a B.S. degree February, 1953, and his M.S. degree June, 1954, in physics from U.C.L.A. At present he is a graduate student at the Institute of Geophysics at U.C.L.A. studying elastic wave propagation.

He held the Shell Fellowship in Geophysics at U.C.L.A. during the academic year 1956–1957.

Mr. Gangi is a member of Sigma Pi Sigma, Institute of Radio Engineers and an associate member of Sigma Xi.

CHARLES F. HADLEY received his B.S. in 1937 and his M.S. in electrical engineering in 1938 from the California Institute of Technology. Upon graduation he was employed by Magnolia Petroleum Company in Dallas, Texas. In 1944 he received a Ph.D. degree in electrical engineering from Stanford University. Upon graduation he joined the staff of Radio Research Laboratory at Harvard University where he was engaged in development of microwave measuring instruments used in the radar countermeasure equipment. In 1946 he joined the staff of the exploration division of the research department of Stanolind Oil and Gas Company in Tulsa. He is now a senior research engineer. He is a member of the Society of Exploration Geophysicists and a Senior Member of the Institute of Radio Engineers.

WAYNE H. JACKSON received the degree of Geophysical Engineer from the Colorado School of Mines in 1951. He was employed by the U. S. Navy Electronics Laboratory in San Diego from 1951 to 1952. Since 1952 he has been a geophysicist with the ground surveys section of the U. S. Geological

HADLEY JACKSON MURPHY RICHTER

Survey. He is a member of the Society of Exploration Geophysicists and the European Association of Exploration Geophysicists.

L. KNOPOFF was born in Los Angeles, California in 1925. He obtained the B.S. degree from the California Institute of Technology in 1944 and the Ph.D. in physics from the same institution in 1949. Since 1950 he has been at the Institute of Geophysics of the University of California where he is now an associate professor.

WILLIAM O. MURPHY, JR., was born in Salt Lake City, Utah. He attended elementary and high school in Utah and was graduated from the University of Utah in 1951, with a B.S. degree in Geophysics. He was employed by the Sohio Petroleum Company for two years and then entered the army. Following his release from the army, he returned to the University of Utah and received a M.S. degree in geophysics in 1957. He is now employed by Standard Oil Company.

Mr. Murphy is an associate member of Sigma Xi and SEG.

LAWRENCE D. PORTER was born in Los Angeles, California on October 5, 1932. He received a B.S. degree in physics from Stanford University in January, 1955. During the summer of 1955 he served as an electronics engineer with Hycon Mfg. Co. in Pasadena, California. In January, 1957, he received a M.S. degree in physics from U.C.L.A. He has been with the Institute of Geophysics at U.C.L.A. since September, 1955.

DONALD H. RICHTER received his B.S. degree in geology from the New Mexico Institute of Mining and Technology in 1950 and his M.Sc. degree in geology from Queen's University in 1952. During the summer of 1951 he was a field geologist in northern Ontario for Jones and Laughlin Steel Corp. and in the summer and fall of 1952 led a geological field party in Newfoundland for Falconbridge Nickel Mines, Ltd. Since 1952 he has been engaged in both field and laboratory studies of mineral deposits with the U. S. Geological Survey in Washington, D. C., Cuba, and Denver, Colorado.

Mr. Richter is a member of the Geological Society of America, the Mineralogical Society of America, and the Geochemical Society.

ENDERS A. ROBINSON attended Massachusetts Institute of Technology where he received a S.B. in mathematics in 1950, a S.M. in economics in 1952, and a Ph.D. in geophysics in 1954. From 1952 to 1954 he directed the MIT geophysical analysis group. During 1954–1955 he was a geophysicist for the Gulf Research and Development Company in Pittsburgh. In 1955 he returned to MIT to teach operations research and statistics in the mathematics department and do research for the

ROBINSON SUTTON SWENUMSON

school of industrial management. The next year he joined the Standard Oil Company (N.J.) in New York as an economist in the coordination division.

Dr. Robinson is an associate member of the Society of Exploration Geophysicists, a member of the Econometric Society, and a contributing editor of *Business Scope*.

GEORGE H. SUTTON received the B.S. degree in physics from Muhlenberg College in 1950, the M.A. degree in geology in 1953 and the Ph.D. degree in geology in 1957 from Columbia University. He then became research assistant and later research associate at Lamont Geological Observatory, where his principal activities have concerned seismic exploration of oceans, earthquake seismology, and marine geophysics. He received the William Bayard Cutting traveling fellowship at Columbia University while seismologist for Institut pour la Recherche Scientifique in Afrique Centrale, Belgian Congo, where he was studying seismicity and gravity anomalies of the Western Rift Valley of Africa.

Dr. Sutton is a member of the Sigma Xi, American Geophysical Union, Seismological Society of America, and Society of Exploration Geophysicists.

GLEN H. SWENUMSON received his B.A. degree from Ohio Wesleyan University in 1948, having majored in chemistry and geology; he is a native of South Dakota. Since graduation, he has been associated with the Continental Oil Company, working successively as geophysical interpreter, party chief, supervisor, and division geophysicist.

Mr. Swenumson is a member of the Society of Exploration Geophysicists, the New Mexico Geological Society, and Roswell Geological Society.

SOCIETY ROUND TABLE

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AGI Glossary

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National Research Council Div'n of Earth Sciences Representative

R. D. WYCKOFF

AAAS Council Representative

ROLAND F. BEERS

LOCAL SECTIONS

Geophysical Society of Tulsa

Chartered February 2, 1948

Frank Searcy, *pres.*
T. S. Green, *1st v-pres.*
F. R. Kittredge, *2nd v-pres.*
P. M. McNally, *treas.*
M. B. Widess, *editor*
S. E. Giulio, *secty.* The Carter Oil Co., Box 801, Tulsa 2, Okla.

Meetings: Monthly, 2nd Thursday, 7:00 P.M., meeting only, University of Tulsa, room 224, Petroleum Science Hall

Houston Geophysical Society

Chartered February 14, 1948

G. P. Montgomery, Jr., *pres.*
J. M. Wilson, *1st v-pres.*
C. C. Sellers, *2nd v-pres.*
J. P. Pascall, *treas.*
E. J. Marti, *secty.* Union Oil Co. of Calif., 800 Prudential Bldg., Houston, Texas

Meetings: Monthly, Noon luncheon ($1.65), Rice Hotel

Pacific Coast Section SEG

Chartered April 12, 1948

Flint H. Agee, *pres.*
C. A. Bengston, *v-pres., N.D.*
Lawrence S. Morrison, *v-pres., S.D.*
William L. Basham, *secty.* Std. Oil Co. of Calif., 325 W. 9th St., Los Angeles, Calif.

Meetings: Monthly, 2nd Thursday, Noon luncheon ($2.00), Biltmore Hotel, Los Angeles

Dallas Geophysical Society

Chartered August 7, 1948
R. E. Rettger, *pres.*
Chester Donnally, *1st v-pres.*
A. W. Musgrave, *2nd v-pres.*
Wm. C. Wooley, *secty.* Magnolia Petroleum Co., Box 900, Dallas, Texas
Meetings: Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Building, Southern Methodist University

Fort Worth Geophysical Society

Chartered August 7, 1948
C. J. Long, *pres.*
O. A. Strange, *v-pres.*
D. T. McCreary, *secty.* The Texas Co., Box 1720, Fort Worth, Texas
Meetings: Monthly, 4th Monday, Noon luncheon ($1.50), Texas Hotel

Ark-La-Tex Geophysical Society

Chartered March 12, 1949
C. P. Bragg, *pres.*
Bill C. Tucker, *v-pres.*
W. E. Martin, *secty.* The Carter Oil Co., 224 Pennsylvania, Shreveport, La.
Meetings: Monthly, last Monday, Noon luncheon ($1.50), Captain Shreve Hotel, Shreveport

Permian Basin Geophysical Society

Chartered January 30, 1950
R. M. Pinson, *pres.*
B. F. Owings, *1st v-pres.*
E. E. Fickinger, *2nd v-pres.*
B. A. Heidt, *treas.*
J. E. Clark, *secty.* Box 1018, Midland, Texas
Meetings: Monthly, 2nd Tuesday 7:30 P.M., free coffee & donuts, Midland Women's Club, Midland, Texas

Denver Geophysical Society

Chartered May 19, 1950
R. C. Kendall, *pres.*
J. E. Thompson, *v-pres.*
C. B. Smith, Jr., *secty.* Continental Oil Co., 3571 Grape St., Denver, Colo.
Meetings: Monthly, 1st Monday, 5:30 P.M., meeting only. Petroleum Club, Denver

Canadian SEG

Chartered January 24, 1952
George J. Blundun, *pres.*
John Fuller, *v-pres.*
Lorne H. Reed, *secty.* Universal Seismic Surveys, Ltd., 223 14th St. N.W., Calgary, Alberta
Meetings: Monthly, no set schedule

Geophysical Society of Oklahoma City

Chartered September 30, 1952
W. B. Robinson, *pres.*
G. E. Anderson, *1st v-pres.*
R. H. Peacock, *2nd v-pres.*
C. L. Howell, *treas.*
H. R. DeVinna, *secty.* Central Exploration Co., 13 NE 28th, Okla. City, Okla.
Meetings: Monthly, 2nd or 3rd Monday. Time and place to be announced

Casper Geophysical Society

Chartered May 23, 1953
Dupree McGrady, *pres.*
R. L. Zieve, *v-pres.*
R. L. Billings, *secty.* Forest Oil Corp., 254 N. Center St., Casper, Wyoming
Meetings: Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming

Geophysical Society of South Texas

Chartered November 9, 1953
Wm. R. Gray, *pres.*
Wm. Harry Mayne, *v-pres.*
Jack W. E. Edmonson, *secty-treas.* 713 First Nat'l Bank Bldg., San Antonio 5, Texas
Meetings: 1st and 3rd Wednesdays, Noon luncheon, Sommers Cafeteria, Main Plaza, San Antonio

Southeastern Geophysical Society

Chartered April 1, 1954
Merrill Smith, *pres.*
Wm. G. Hasen, *v-pres.*
G. F. Berry, *secty.* 203 Carondelet Bldg., New Orleans, Louisiana
Meetings: Monthly, 3rd Monday, Noon luncheon ($1.50), St. Charles Hotel, New Orleans

Montana Geophysical Society

Chartered April 12, 1954
Jack W. Peters, *pres.*
C. F. Moore, Jr., *1st v-pres.*
Phillip I. Hendricks, *2nd v-pres.*
Ward T. Langstroth, *secty-treas.* The Carter Oil Co., Box 1982, Billings, Montana
Meetings: Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club

Jackson Geophysical Society

Chartered May 12, 1955
Fred Forward, *pres.*
W. J. Robinson, *v-pres.*
R. Long, *secty.* Stanolind Oil & Gas Co., 1166 Raymond Road, Jackson, Mississippi
Meetings: Monthly, during 3rd week, 5:30 P.M., refreshments, 6:30 P.M., dinner ($2.00), Roof Garden of Robert E. Lee Hotel, Jackson, Mississippi

Southwest Louisiana Geophysical Society

Chartered January 4, 1956
John W. Bell, Jr., *pres.*
A. V. Hargis, *1st v-pres.*
W. W. Daly, *2nd v-pres.*
Lawrence N. Ott, *secty.* Tidewater Oil Co., Box 1147, OCS, Lafayette, Louisiana
Meetings: to be announced

Utah Geophysical Society

Chartered October 29, 1956
T. E. Hobbs, *pres.*
J. R. Cheney, *1st v-pres.*
K. L. Cook, *2nd v-pres.*
John W. Erwin, *secty.* 600 Crandall Bldg., Salt Lake City 1, Utah

Dakota Geophysical Society

To be chartered
W. E. Phillips, *pres.*
Hugh McCain, *1st v-pres.*
Quin Hayes, *2nd v-pres.*
R. R. Phair, *secty.* Roundup Powder Company, Box 452, Bismarck, North Dakota
Meetings: Monthly, 1st Friday, 7:30 P.M., Petroleum Club, Prince Hotel, Bismarck, North Dakota

STUDENT SOCIETIES AFFILIATED

Colorado School of Mines Society of Student Geophysicists

John M. Perrigo, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado
Meetings: to be announced

Geophysical Society of Saint Louis University

Wm. Reeves, *secty.* Saint Louis University, 3621 Olive Street, St. Louis 8, Missouri
Meetings: Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology

SEG Houston Student Section

Reed B. Kubena, *secty.* Box 6527, Houston, Texas
Meetings: to be announced

University of Toronto Geophysical Society

John E. Hogg, *secty.* 49 St. George Street, Toronto 5, Ontario
Meetings: Bi-weekly, alternate Thursdays, 4:00 P.M., 49 St. George Street

University of Tulsa Student Geophysical Society

Vernon Malahy, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma
Meetings: Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section

John T. Semple, Jr., *secty.* Box 56, Texas Western College, El Paso, Texas
Meetings: to be announced

Pennsylvania State University Geophysical Society

Wm. R. England, *secty.* College of Mineral Industries, University Park, Pa.
Meetings: to be announced

University of Utah Geophysical Society

Howard L. Confer, *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah
Meetings: Monthly, 1st Thursday, Noon, Mines Building. Other special meetings to be announced

Georgia Institute of Technology Geophysical Society

William Hogarth, *secty.* Box 4748, Atlanta, Georgia
Meetings: to be announced

A & M College of Texas Student Geophysical Society

Robert T. Smith, *secty.* Geology and geophysics dept., A & M College of Texas, College Station, Texas

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the name of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

Helmut N. Altmann (A. Loehnberg, E. Loehnberg, Michael Baer, Dr. Eug. Unz)
G. E. Archie
Theodore Ludwig Babirack (Dean Walling, V. E. Prestine, H. D. McGrady)
W. G. Caughlin (O. B. Manes, A. B. Wood, J. R. Randolph, C. B. Stone)
John L. Coleman (C. A. Wachter, J. F. Judson, J. E. Dorris, O. L. Taylor)
E. Allen Cook (R. D. Lynn, Norman H. Ricker, Henry B. Ferguson, Wm. A. Sorge)
J. Duncan Crone (A. A. Brant, H. O. Seigel, K. E. Hunter, A. M. Bell)
J. R. Everett (Hubert L. Schiflett, Howard Smith, Roy O. Smith, John W. Byers)
Graham W. Fenner (E. L. Mount, D. S. Goldshalk, F. L. Searcy)
William T. Graves (Chester Sappongton, K. R. Wells, R. E. Wright, Henry Werth)
Stanley W. Hall (F. J. DiGuilio, J. W. Miller, Craig Ferris)
Joseph Keselik (A. J. Barthelmes, R. W. Mossman, H. R. Breck, R. B. Baum)
Ernest A. Laugpaul (R. S. Finn, J. T. Murrell, C. E. McClure, J. L. Ferguson)
Charles D. Lewis (J. D. Delbridge, V. E. Whitney, R. H. Peacock, C. A. Wood)
James W. Mann (Chester Sappington, Henry C. Werth, K. D. Kubik, K. R. Wells)
Henry A. Maeder (Dayton Clewell, Thomas J. Bevan, W. Jacques Yost, Ed M. Handley)
Francisco Montiel (Rodolfo Martin, Salvador A. Alvarez Berros, Ed Stulken)
W. E. Moore, Jr. (J. B. Nichols, Guy M. Ratliff, W. O. Clark, John W. Bell)
Donald L. Payne (W. H. Courtier, F. H. Morris, R. A. Hartenberger)
Alex H. Pegues, Jr. (K. G. McCann, W. L. Audas, J. E. Froelich, F. J. Kelly)
William F. Rascher (J. W. Mathews, R. J. Wells, Nolen A. Webb)
Joe J. Robnett, Jr. (J. R. Mahan, J. C. Porter, H. C. Kriegel, Otis T. Halliday)
W. Stemmler (John C. Baxter, C. J. Frankovitch, Henry B. Sawatzky)
Norman R. Tabor (J. E. MacGregor, J. A. Harris, John R. Reese, Gordon M. Frey)
E. B. Tickell (Henry Salvatori, George E. Wagoner, V. E. Prestine, Dean Walling)
William A. Wiebenga (R. F. Thyer, K. Vale, E. J. Polak, L. C. Pakiser)
Carl R. Wischemyer (D. P. Carlton, W. M. Rust, R. R. Thompson)
Thomas C. Yates (W. H. Roane, Warren Collins, Delbert Smith, G. D. Gibson)

APPLICATIONS FOR TRANSFER TO ACTIVE MEMBERSHIP

W. E. Blakely (M. B. Dobrin, R. A. Boulware, J. H. Frasher)
Roger L. Brown (James E. Walker, E. M. Curry, Kenneth S. Cohick)
John W. Burk (H. M. Thralls, J. G. Jackson, T. S. Green)
W. E. R. Clements (R. E. Doe, H. E. Stommell, J. W. Hoover)
Douglas D. Goddard (S. K. Van Steenbergh, Leycester Stanley, W. D. Neff)
R. H. Lommen (J. E. Walker, Victor J. Blum, G. W. Oistma)
Donald L. Olson (Maurice Sklar, John Sloat, Walter Fillippone, Flint Agee)
David R. Scheel (E. R. Kinsley, A. J. Caan, R. H. Rainey)

COMMITTEE REPORT

GEOPHYSICAL ACCIDENT INFORMATION EXCHANGE

The Geophyscial Accident Information Exchange is composed of a group of oil companies' geophysical departments and geophysical contractors who exchange accident information with each other on a voluntary basis under the sponsorship of the SEG Standing Committee on Safety. The exchange of information takes place monthly on an anonymous basis and is handled by a disinterested party who acts as agent. Each participant sends his information to the agent who simply compiles, duplicates and distributes the total information to those companies that are currently members of the Exchange. Company names are not mentioned, but the information sent in by each company is grouped and separated from that sent by others. When a participating company has had no reportable accidents and so reports, this is also noted without mentioning the name of the company.

Reports submitted to the Exchange need not be in any special form but merely a readable account of the accident. Reports are not limited to disabling injury accidents, because often the difference between a non-injury or minor injury accident and one involving disability is very small.

Currently thirty-five companies are participating in the Exchange and approximately twenty companies submit regular monthly accident information. Many participants use the information from the Exchange to plan and guide their accident prevention program. A study of the information for several months shows a surprising regularity of various types of accidents that happen on geophysical crews. They appear to fall into definite groupings which make it possible to take active steps to prevent or minimize those accidents in the future. Obviously the more accidents reported and the more details supplied, the greater is the experience available to the subscriber.

Membership in the Exchange is entirely voluntary, and any organization in the geophysical business may join by requesting an enrollment form from:

Accident Information Exchange
Post Office Box 645
Tulsa 1, Oklahoma

Each participant is charged $2.00 per month, payable six months in advance, for cutting the stencils, duplicating and mailing a single copy of all the information for the month to the participant. If additional copies are wanted, they will be furnished at one cent per page.

The Standing Committee on Safety invites you to use this Exchange as a tool in your accident prevention program.

ANNOUNCEMENTS

MEMORIALS HONOR FATHER MACELWANE

Since the death of the Rev. J. B. Macelwane, S.J., several memorials at the Saint Louis University Institute of Technology have been established, and others are being contemplated. For the information of many SEG members who may wish to participate in these projects, the following is a report by the Rev. V. J. Blum, S.J., Dean of the Institute.

"To date several (memorials) have been set up or are being discussed by friends, students, and alumni. These are:

"1. 'The Father James B. Macelwane Annual Awards in Meteorology.' This is a cash award for first, second, and third prize for the three best papers on some phase of meteorology submitted by classified students in colleges and universities. The total sum available for these annual awards is $250.00 per year. The money will be given by the Weather Corporation of America. The awards are to be made through the sponsorship of the American Meteorological Society which is now considering the matter for formal approval.

"2. Recently money was given the Institute of Technology for an endowment to supply annual funds for awards to Seniors in the Institute whose scholastic achievement has been of superior quality. These will be known as the 'Father Macelwane Achievement Awards.' Although these awards will

take the simple form of a plaque, we would like to expand the endowment fund by several thousand dollars so as to make it possible to give this award to a Senior in each field of study, i.e., one for the geophysical engineering class, one for the electrical engineering class, etc.

"3. Shortly after Father passed away a number of his friends sent in money to be used to honor the memory of his name. This money was used to establish the 'Reverend James B. Macelwane, S.J., Loan Fund.' This is a fund from which students in the Institute of Technology may draw interest-free small loans for short periods of time. This fund might be expanded by several hundred dollars.

"4. One of the first cash gifts to be applied toward the proposed new building of the Institute of Technology was designated for furnishing and decorating the Board Room. This will be known as the 'Macelwane Board Room.'

"We would very much like to see someone honor Father Macelwane by (say) paying for the geophysical laboratories space in the new building. This would constitute a sizeable gift.

"5. The Institute of Technology Alumni Association has a committee working on a project to honor Father. I do not know what the nature of the project is; it seems to be concerned with an endowment fund for a Macelwane Fellowship.

"6. In addition to possible contributions to the proposed new building of the Institute of Technology, the University considers that endowment funds for a 'Macelwane Professorial Chair' would constitute a very worthy memorial to Father Macelwane."

For further information write to Rev. V. J. Blum, S.J., Dean, Institute of Technology, Saint Louis University, 3621 Olive Street, St. Louis 8, Missouri.

THREE NEW LABORATORIES OPENED BY GULF OIL CORP.

Gulf Oil Corporation has opened three new laboratories designed to accelerate the exploration of new frontiers of petroleum science. With a combined multi-million dollar value, the facilities measurably expand the scope of the company's 53-acre Research Center at Harmarville, Pa.

The intricately instrumented new structures will spearhead research into improving methods of oil production and the handling of well fluids; into bettering fuels and lubricants for automotive, aviation and marine engines; and into application of nuclear energy to all phases of petroleum science.

Five days of receptions for special groups were set aside to open the new structures. These began May 28, 1957 with a press inspection for which 150 editors and reporters gathered from throughout the U. S.

Dedication ceremonies, held the following day, were keynoted by Gen. Matthew B. Ridgway, World War II hero, commander of U. S. and United Nations forces in the Korean War, former chief of staff, U. S. Army, and presently chairman of the board of trustees of Mellon Institute, Pittsburgh. Gulf President William K. Whiteford officially christened the new structures; and Dr. Blaine B. Wescott, Gulf vice-president—research, presided. The Gulf board and some 500 business and civic leaders from throughout the nation were guests.

After an intermission for the Memorial Day week-end, an Educators Day followed on June 3, when professors of leading scientific collges throughout the nation toured the Center. Later they were guests at a banquet tendered by the officers, where Carnegie Tech President, Dr. J. C. Warner, spoke.

On June 4, the Center was opened to Gulf employee families, and on June 5 and 6 to residents of Allegheny River Valley communities in the near neighborhood. Nearly 100 exhibits, a number in animated form, and scores of explanatory signs, were set up to clarify the Research Center activities to non-scientific guests.

Interest throughout the five-day ceremonies centered on the new laboratories, each equipped with the latest resources of the scientific world and each notably extending the horizons of the 44-building Research Center in its particular sphere.

The new buildings comprise the William Larimer Mellon Production Research Laboratory and Drilling Building, where new drilling and oil production methods are being investigated; the Richard Beatty Mellon Automotive Products Laboratory, one of the world's most advanced centers for fuel and lubricant testing; and the Andrew William Mellon Nuclear Science Laboratory, in which uses of nuclear energy in the petroleum industry will be studied.

INDUSTRIAL ARTS INDEX TO INCLUDE GEOPHYSICS

The H. W. Wilson Company, publisher of the widely used *Reader's Guide to Periodical Literature* and *The Industrial Arts Index*, has announced that GEOPHYSICS will be indexed regularly in the new *Applied Science and Technology Index*. In a letter to the Society's Editor the company advised that GEOPHYSICS was chosen in response to popular demand from their subscribers, and that indexing would begin with the January, 1958 issue of the SEG Journal.

This announcement was received with enthusiasm by the Society's Editor and the Business Manager, who agree that the Society may be proud of its official Journal. It is expected that GEOPHYSICS will enjoy a considerable increase in readership outside the Society membership.

GEOPHYSICS is also indexed regularly by The Engineering Index, Inc., a publication of the Engineering Societies Library.

10TH ANNIVERSARY OF THE CHARTERING OF LOCAL SECTIONS TO BE COMMEMORATED

The 1958 volume of *The Proceedings of the Geophysical Society of Tulsa* will be dedicated to the Local Sections by commemorating the 10th anniversary of chartering of Local Sections by the SEG. According to M. B. Widess, Editor of the *Proceedings*, all Local Sections will be approached for abstracts of papers presented at their respective meetings during the season 1957–1958, and for a summary of their activities during that period.

The stated objective of the issue is to offer service both by disseminating professional information through the publication of the abstracts and by familiarizing each Local Section with activities of other Local Sections. The *Proceedings*, an annual journal then going into its fifth volume, wishes thus to place itself at the service of Local Sections for publication of material of national professional interest that is not adaptable to publication in GEOPHYSICS.

HOUSTON GEOPHYSICAL CLUB ORGANIZES

After nearly two years of careful planning, Houston area geophysicists and supply men last month were enjoying a new social and professional club for their group.

The Houston Geophysical Club, conceived by a group of local geophysicists, opened at the end of April in luxurious quarters in Houston's southwest area, center of Houston's—and the world's—geophysical business activities.

After a month of operation, the club's membership has increased from 130 to nearly 250, directors of the club reported. They expect that the charter membership of 300 will be attained within 60 days.

Upper limit is presently set at 600 members. To preserve a professional community of interest, the club's by-laws have established membership in local or national sections of SEG as a prerequisite to joining the Houston Geophysical Club.

Membership may be obtained by geophysicists not resident in the Houston area, the club management reported. Non-resident memberships are provided for in both transferable and non-transferable classifications.

James A. Treybig, division geophysicist for The Texas Company in Houston, is president of the club. Other officers include John W. Byers, first vice-president; Lewis B. Rogers, vice-president; Richard I. Maddox, secretary; and Ernest A. Pratt, treasurer. Anthony J. Lala is general manager.

The nine-man board of directors is headed by E. Joe Shimek, chairman. Members are James A. Brooks, Mike C. Huber, Charles H. Huffman, Charles C. Sellers, Harrison E. Stommel, James A. Treybig, and Lawrence C. Twining.

Al Musgrave, left, of the Dallas Geophysical Society, chats with future engineer David MacPherson and John W. Larson, design engineer for Chance-Vought Aircraft, at the annual dinner for future engineers sponsored by the Engineers Club of Dallas on April 25, with Dallas Geophysical sponsoring some of the 300 high school seniors attending. Each boy sat with a sponsor from his future field.

PERSONAL ITEMS

THE BOARD OF REGENTS of The University of the South, at Sewanee, Tennessee, awarded HENRY C. CORTES, vice-president and director of Magnolia Petroleum Company, the Honorary Degree of Doctor of Science at commencement exercises June 10, 1957.

Cortes, a native of Houston, Texas, attended Sewanee Military Academy and The University of the South.

He now has management charge of co-ordinating Magnolia's offshore operations and of the company's Field Research Laboratory near Dallas.

In 1924, Cortes was employed by the Vacuum Oil Company in the geological department and engaged in exploration work for them throughout the Gulf Coast area of Texas and Louisiana.

When Vacuum merged with Standard Oil Company of New York to form Socony-Vacuum Oil Company in 1932, Henry Cortes became affiliated with Magnolia. Magnolia is the southwestern affiliate of Socony Mobil Oil Company, Inc. Five years later he was named director of geophysics, and in June, 1946, was made assistant manager of the Exploration Division. He was elected to the board of directors and named executive in charge of the organization's Field Research Laboratory in March, 1954. On August 22, 1956, he was made a vice-president of Magnolia Petroleum Company.

Dr. Cortes' familiarity with the developing sciences of petroleum geology and geophysics led to his having a large part in the locating of several oil fields in the coastal areas of Louisiana and Texas.

As company director in management charge of Magnolia's Field Research Laboratory, Cortes helped set the course for the fundamental and applied research undertaken by one of the petroleum industry's major centers for exploration and production experimentation. The Laboratory has made significant contributions in geological, geophysical and production research and engineering.

The Geophysical Case Histories series of SEG, now in its second volume, owes its existence to the work of Dr. Cortes, who was the first chairman of the case histories committee.

In June, 1955, his knowledge of geophysics in offshore areas led to his presentation of a paper on "Geophysical Prospecting Over Continental Shelves" at the Fourth World Petroleum Congress in Rome, Italy.

Henry Cortes is a past president of the Society of Exploration Geophysicists, Dallas Geological Society, and Dallas Petroleum Club. He is a Fellow of the Texas Academy of Science. Cortes is also a member of the American Association of Petroleum Geologists, American Geophysical Union, American Association for the Advancement of Science, Seismological Society of America, and Dallas Geophysical Society.

MAURICE EWING has received the William Bowie Medal of the American Geophysical Union. Presentation was made April 30, 1957, after a citation by BENO GUTENBERG. The citation and response by Dr. Ewing appear in *Transactions American Geophysical Union*, v. 38, n. 3 (June, 1957).

ADDISON L. BARNES has been appointed vice president of Southern Geophysical Company, and will be based at the firm's Midland offices. The appointment was announced by DR. SIDON HARRIS, president of the Fort Worth firm, effective May 23, 1957. Dr. Harris stated that Mr. Barnes will direct seismic operations in the Permian Basin and related areas.

ROBERT L. KIDD, president of Cities Service Oil Co. at Bartlesville, has been named a director of the First National Bank and Trust Co. of Tulsa, Oklahoma.

D. D. MIZE, general manager of Electro-Technical Labs. division of Mandrel Industries, Inc., and vice-president of Mandrel, has announced the appointment of Joe J. Du Rapau as his assistant. Mr. Du Rapau will assist Mr. Mize in the sale of Electro-Tech products.

TWO SUBSIDIARIES of Pan American Petroleum Corp. operating in the Caribbean area have taken new names. Jamaican Stanolind Oil Co. has become Pan Jamaican Oil Co. Pan Jamaican holds prospecting licenses on the entire island of Jamaica and its tidelands. Its first two exploratory wells were dry and abandoned. Its third, West Negril No. 1, will soon begin drilling operations.

Venezuelan Pan American Petroleum Corp. has become Pan Venezuelan Oil Co. Pan Venezuelan has been and is conducting surface geological and geophysical operations in eastern and western Venezuela, chiefly in varying joint account operations with other oil companies active in the country. At the last awarding of concessions, Pan Venezuelan was the successful bidder for full or undivided interests in several concessions.

The third Pan American subsidiary in the Caribbean, Cuban Stanolind Oil Co., will retain its name for the present. Cuban Stanolind has drilled two dry holes and has announced plans for an offshore venture in sout-coastal waters. Cuban Stanolind holds about 16 million acres of concession rights in Cuba and in certain offshore areas.

C. E. WILLIAMS, formerly seismic supervisor of the geophysical operations units of Sohio Petroleum Company based in Houston, Texas, has been transferred to Sohio Petroleum Company foreign operations division in Oklahoma City as geophysicist.

EUGENE F. BANGS, a development engineer with Aero Service Corp., Philadelphia, died in Philadelphia on June 22 of bronchial pneumonia. Previously he had been associated with Aero Service Corp. (Mid-Continent) and with Frost Geophysical Company, both of Tulsa.

A graduate of Oklahoma A & M, Bangs played a significant part in the development of the airborne magnetometer. At the time of his death, he was at work on improvements and modifications of Shoran, electronic distance measuring device.

Survivors include his wife, Betty L., and a daughter, Judy, and his parents, Mr. and Mrs. C. E. Bangs of McAlester, Oklahoma. The funeral was held at McAlester on June 25.

Bangs was a member of the American Geophysical Union, the Institute of Radio Engineers, the American Society of Photogrammetry, and the Geophysical Society of Tulsa.

THE TRANSFER OF THE SOUTHERN DIVISION headquarters of Seismograph Service Corporation, world-wide seismic exploration firm, from Tulsa to Houston was announced today by G. H. Westby, president.

Westby announced that Robert B. Baum, assistant vice-president, will be in charge of the southern division, with offices in the Texas National Bank Building.

THOMAS R. SHUGART, formerly an independent oil exploration consultant, has joined D. D. Feldman Oil & Gas at 3200 Republic Bank Building, Dallas, Texas. He will serve as Exploration Manager of the Company.

ELMER F. BLAKE has rejoined Southern Geophysical Company as vice-president in charge of Rocky Mountain operations with headquarters in Denver.

ROBERT DAVENPORT and J. W. RUPERT have organized the Wyoming Seismograph Company, Box 631, Casper, Wyoming, to work in the Rocky Mountain area.

EARL M. WEAVER has left the employment of Herb J. Hawthorne, Inc. after ten years of service to open an office as a consultant at 3751 Aberdeen Way, Houston 25, Texas.

L. F. IVANHOE, consulting geologist-geophysicist, has established a domestic and foreign technical consulting service at 2810 Elmwood Avenue, Bakersfield, California.

ALFRED LOEHNBERG has been appointed by UNESCO to work at the Instituto de Ciencia Aplicada in Mexico, D. F. He will carry out groundwater research and consult the Mexican Government ,n projects of water development. He will also be in charge of geophysical surveys for water."
i

NELSON K. MOODY, former chief geophysicist for Seismograph Service Corporation of Mexico, has been transferred to Tulsa to head the new seismic replay division at SSC's headquarters.

ROY F. BENNETT, President of the Society of Exploration Geophysicists and formerly chief geophysicist for Sohio Petroleum Co., is now foreign exploration manager of Sohio. His office remains at 1351 Skirvin Tower, Oklahoma City.

LEE C. LAMAR has been transferred from the position of division exploration manager of The Carter Oil Company at Billings, Montana, to the Standard Oil Company (N. J.) where he will be regional geologist for North America, Central America and the East Indian Islands. His headquarters will be Room 2751, 30 Rockefeller Plaza, New York City.

H. W. STRALEY III has moved his offices from 1122 Mercer Street to the Seneca Trail Building, Honaker Avenue and Walker Streets in Princeton, West Virginia.

THE APPOINTMENT OF R. J. GRAEBNER to the post of geophysicist for U. S. and Canadian operations of Geophysical Service Inc. has been announced by GSI vice president R. C. DUNLAP, JR.

J. E. FINLEY, Houston, Texas, has been promoted to the newly created position of assistant regional manager of exploration for Continental Oil Company's southwestern region, with headquarters in Fort Worth. He formerly was assistant to the manager of Conoco's headquarters geophysical section at Houston.

CALENDAR OF MEETINGS

1957

October

6– 9 Society of Petroleum Engineers of AIME, Fall Meeting, Adolphus, Baker, and Statler Hilton Hotels, Dallas, Texas.

17–18 Southern California Petroleum Section AIME, Fall Meeting, Biltmore Hotel, Los Angeles, California.

24–26 Acoustical Society of America, Ann Arbor, Michigan (Wallace Waterfall, 57 East 55th St., New York 22, N. Y.)

November

4– 6 Geological Society of America Annual Meeting, Atlantic City, New Jersey.

6– 8 Gulf Coast Association of Geological Societies, Seventh Annual Convention, Roosevelt Hotel, New Orleans, Louisiana.

7– 8 Pacific Coast Section SEG, Autumn Meeting, Ambassador Hotel, Los Angeles, California (J. A. Hugus, Western Gulf Oil Co., 900 Wilshire Blvd., Los Angeles, California)

11–14 Society of Exploration Geophysicists, 27th Annual Meeting, Statler-Hilton Hotel, Dallas, Texas (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

11–14 American Petroleum Institute, 37th Annual Meeting, Conrad Hilton Hotel and Palmer House, Chicago, Illinois.

December

26–31 American Association for the Advancement of Science (Raymond L. Taylor, AAAS, 1515 Massachusetts Ave., Washington 5, D. C.)

1958

March

10–13 American Association of Petroleum Geologists, 43rd Annual Meeting, Biltmore Hotel, Los Angeles, California (E. Harold Rader, Standard Oil Company of California, 605 W. Olympic Blvd., Los Angeles 15, California)

April

17–18 Society of Exploration Geophysicists, Eleventh Annual Midwestern Meeting, Tulsa, Oklahoma (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

October

13–16 Society of Exploration Geophysicists, 28th Annual Meeting, Hotel Gunter, San Antonio, Texas (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

1959

November

9–12 Society of Exploration Geophysicists, 29th Annual Meeting, Biltmore Hotel, Los Angeles, California (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

1960

November

7–10 Society of Exploration Geophysicists, 30th Annual Meeting, Moody Convention Center, Galveston, Texas (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

1961

November

5–9 Society of Exploration Geophysicists, 31st Annual Meeting, Denver, Colorado (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

* * * * *

July 1, 1957 to December 31, 1958

International Geophysical Year (Worldwide) *vide* GEOPHYSICS, v. 21, p. 257–259, and v. 21, p. 681–690 (H. Odishaw, National Academy of Sciences, Washington 25, D. C.)

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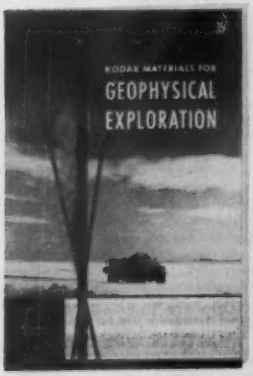

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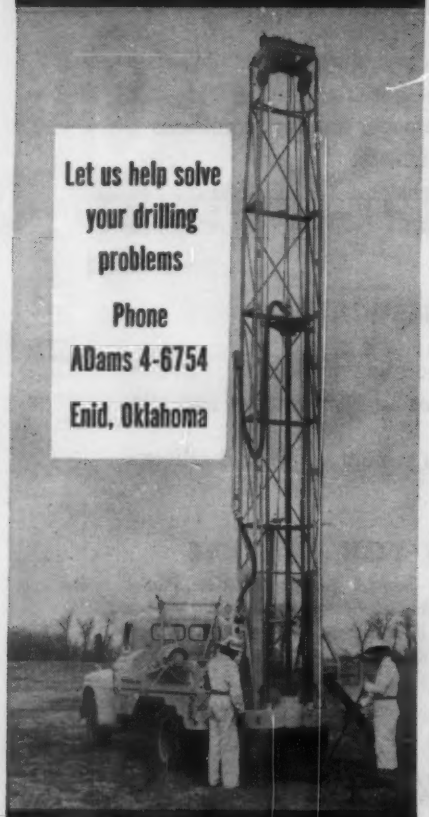

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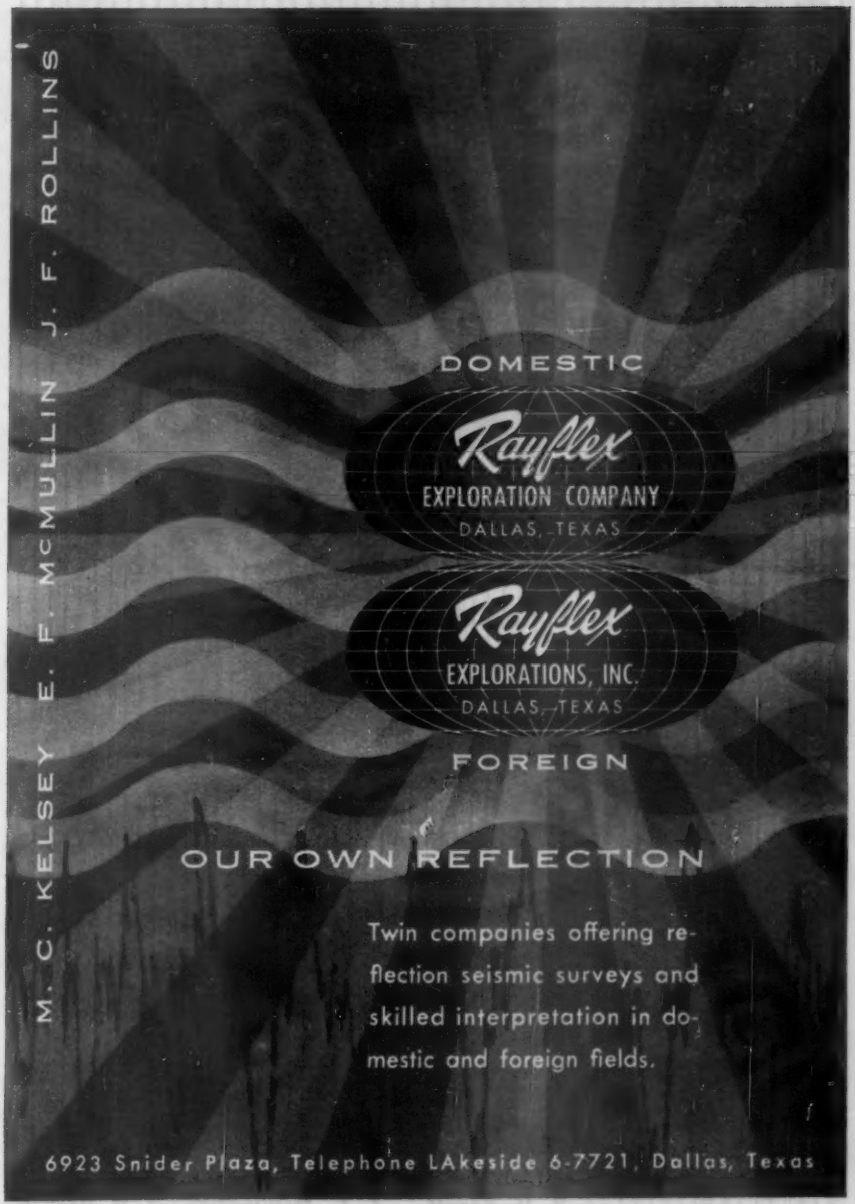
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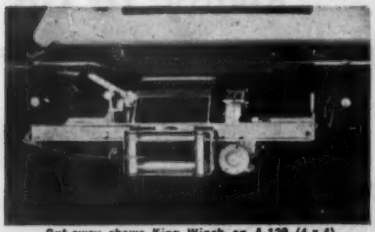

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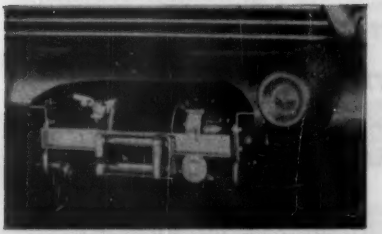

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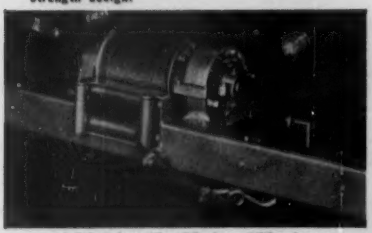

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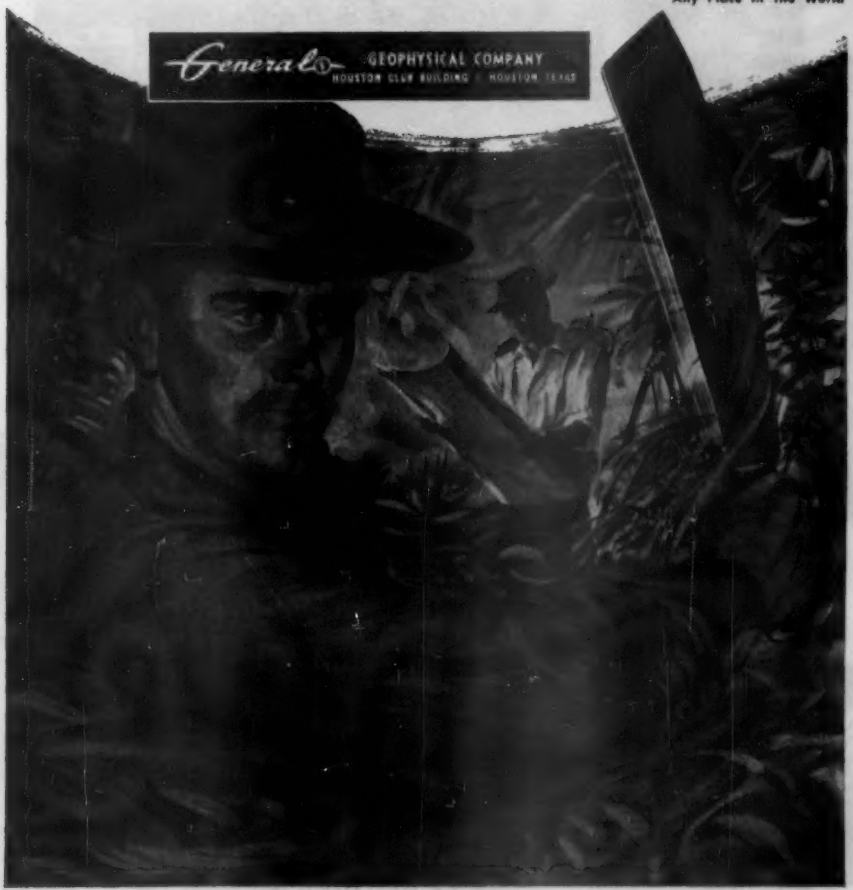

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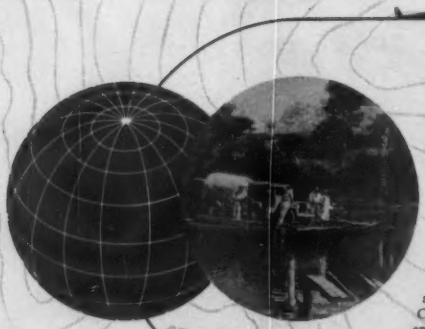

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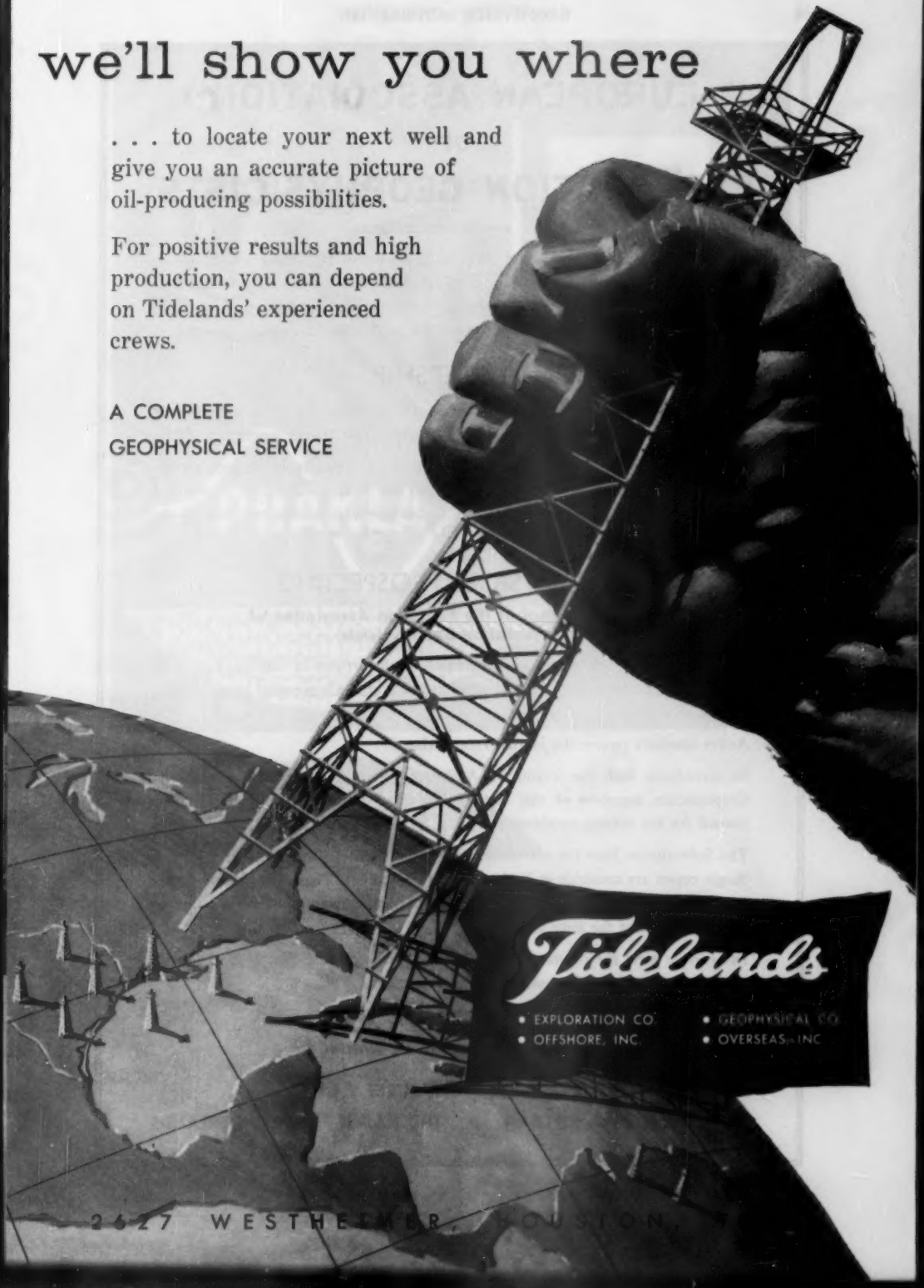

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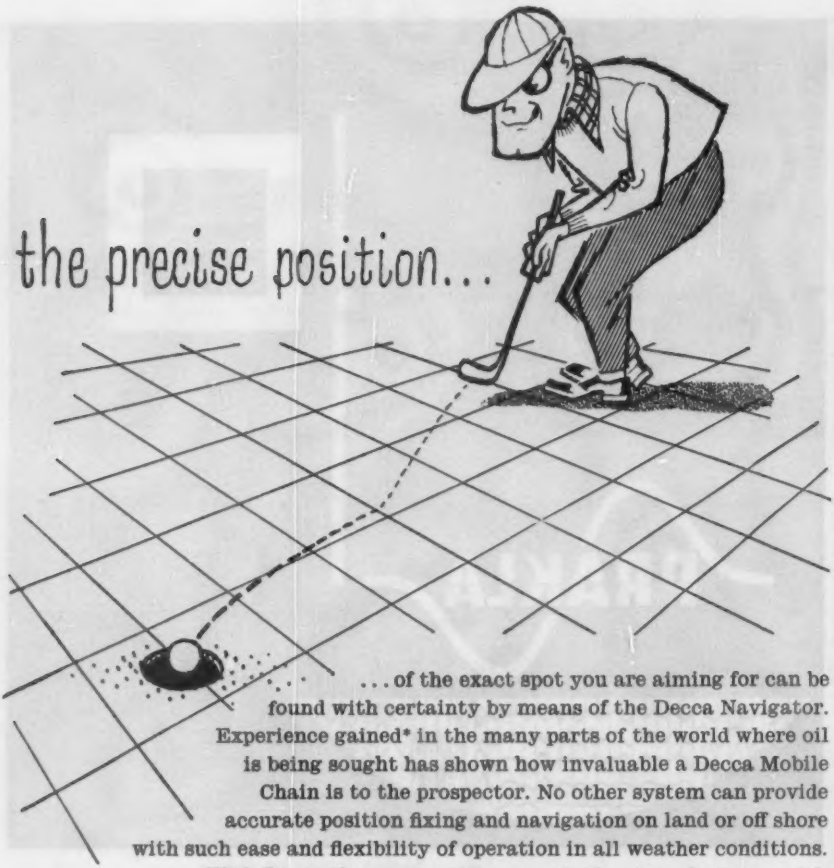

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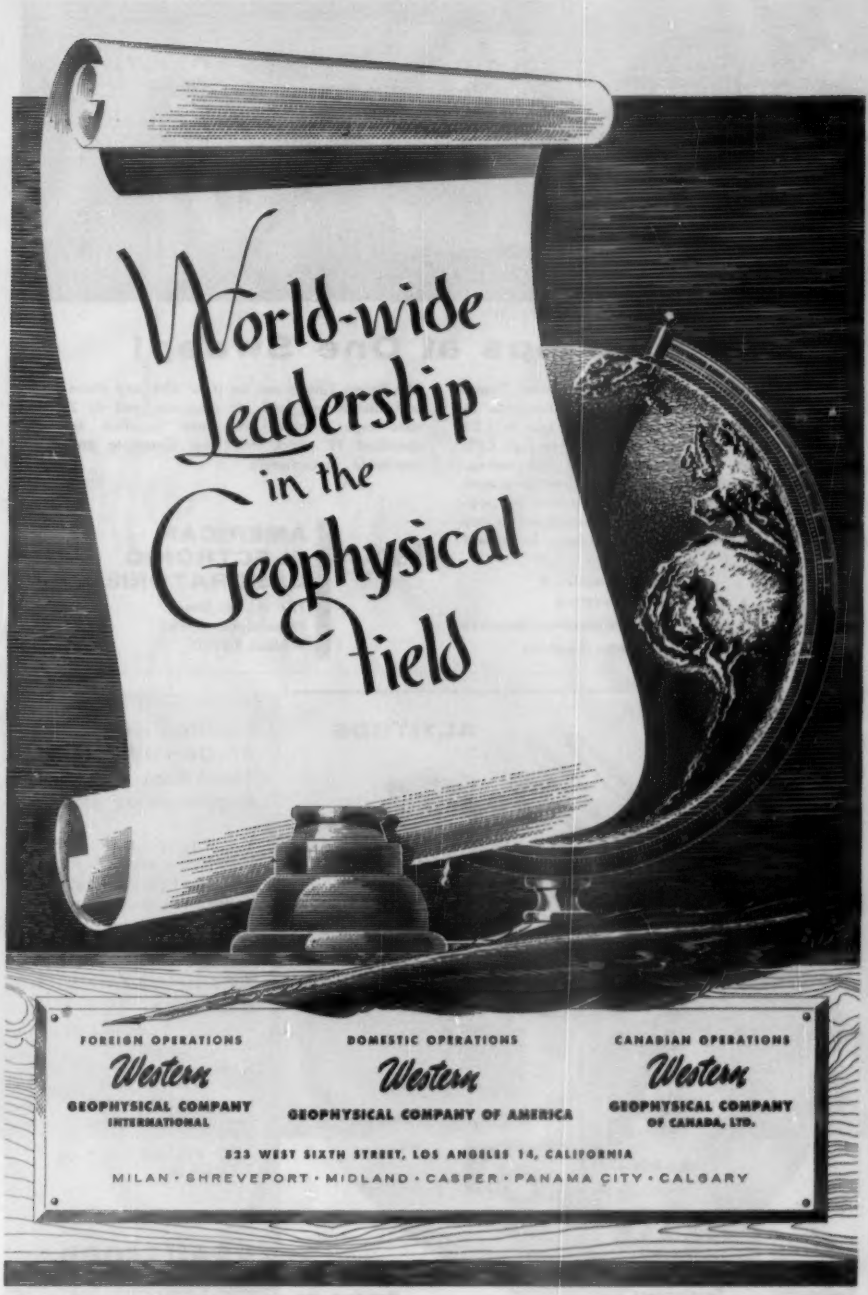

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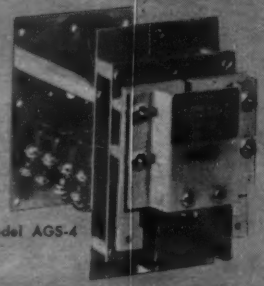

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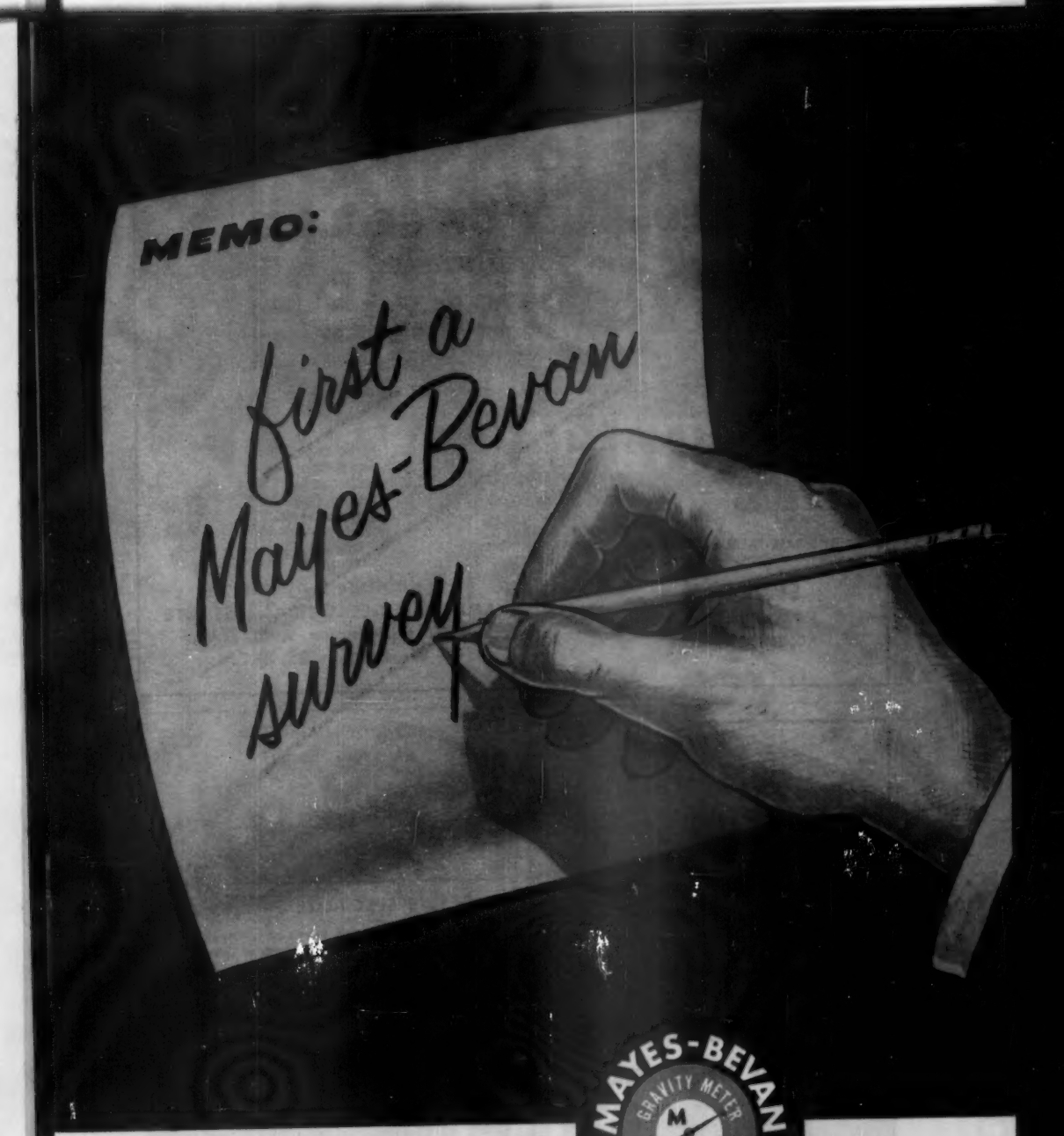

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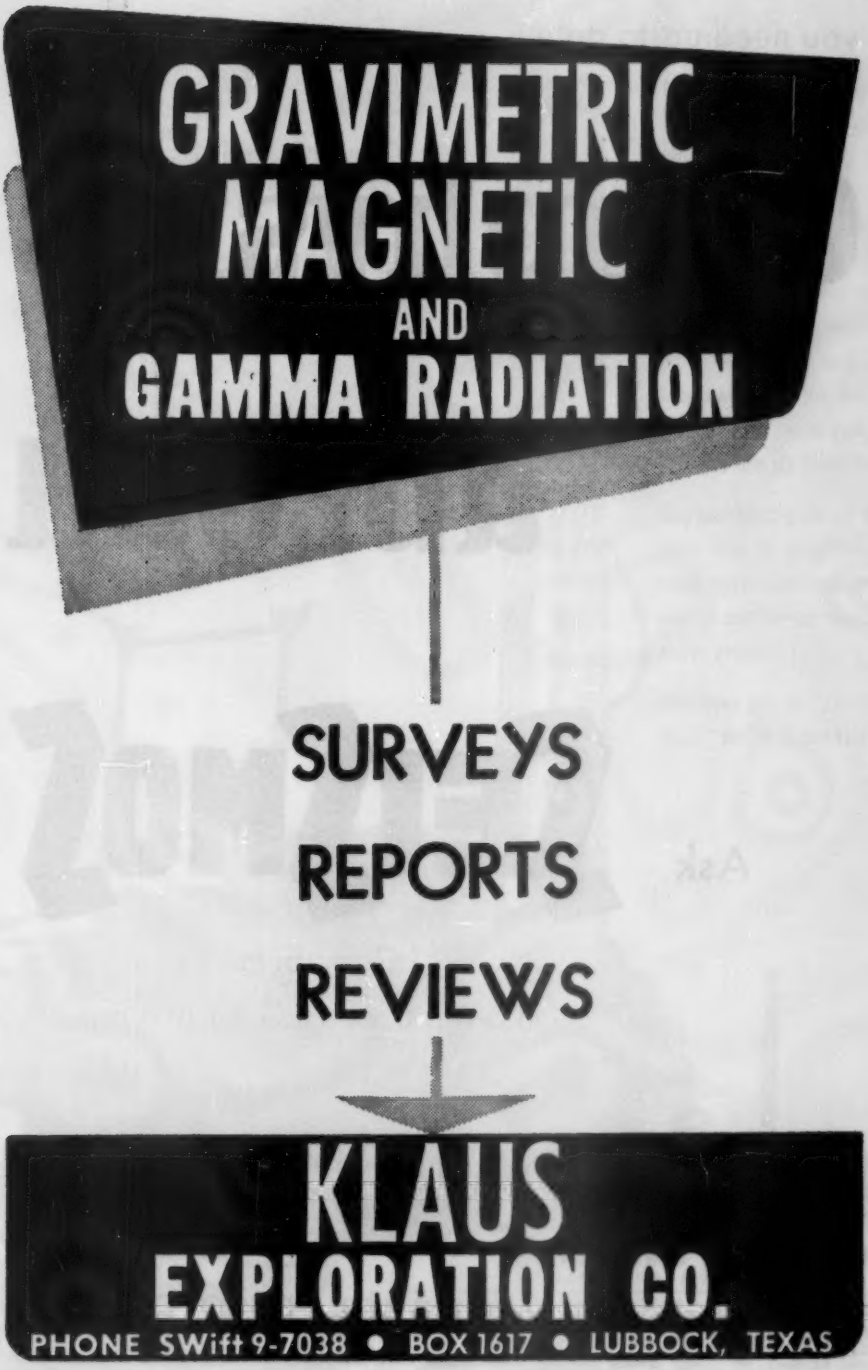

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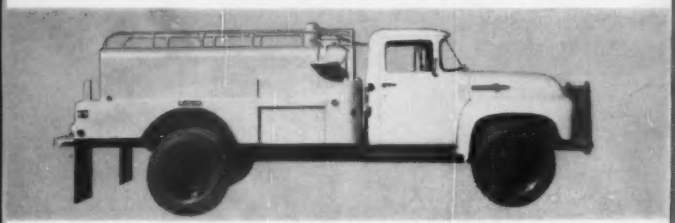

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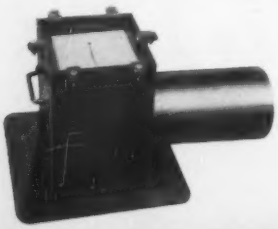

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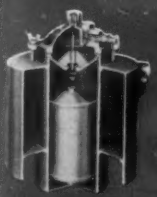

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It has always been Hercules' aim to provide its customers with the best in modern materials and technical know-how. We believe the development of heavy-gauge steel containers for Vibronite®-B—a nitro carbo nitrate blasting agent—is another example of how continuing evaluation of your needs results in means for improving the efficiency of your operations.

Designed in the Hercules Research Center after careful study of actual offshore requirements, these new, improved steel containers meet all prospecting requirements included in reflection and refraction shooting.

Hercules representatives welcome the opportunity to discuss with you how Vibronite-B packed in these modern containers can assist in your seismic work.

XR56-8

Technical Data

Vibronite-B is packed in distinctive, light blue containers of heavy-gauge steel to withstand transportation, handling, and storage conditions, and to prevent water and moisture penetration. They have a density greater than salt water, which eliminates all possibility of floating charges. These completely new containers are also equipped with large bails and recessed ends to facilitate loading and unloading in the holds of boats, and to provide convenient handling by shooting crews. Hercules Vibronite-B is now available in five container sizes: 8 inches by 50 pounds; 8 inches by 40 pounds; 5½ inches by 25 pounds; 4½ inches by 16⅔ pounds; and 4½ inches by 10 pounds.

HERCULES

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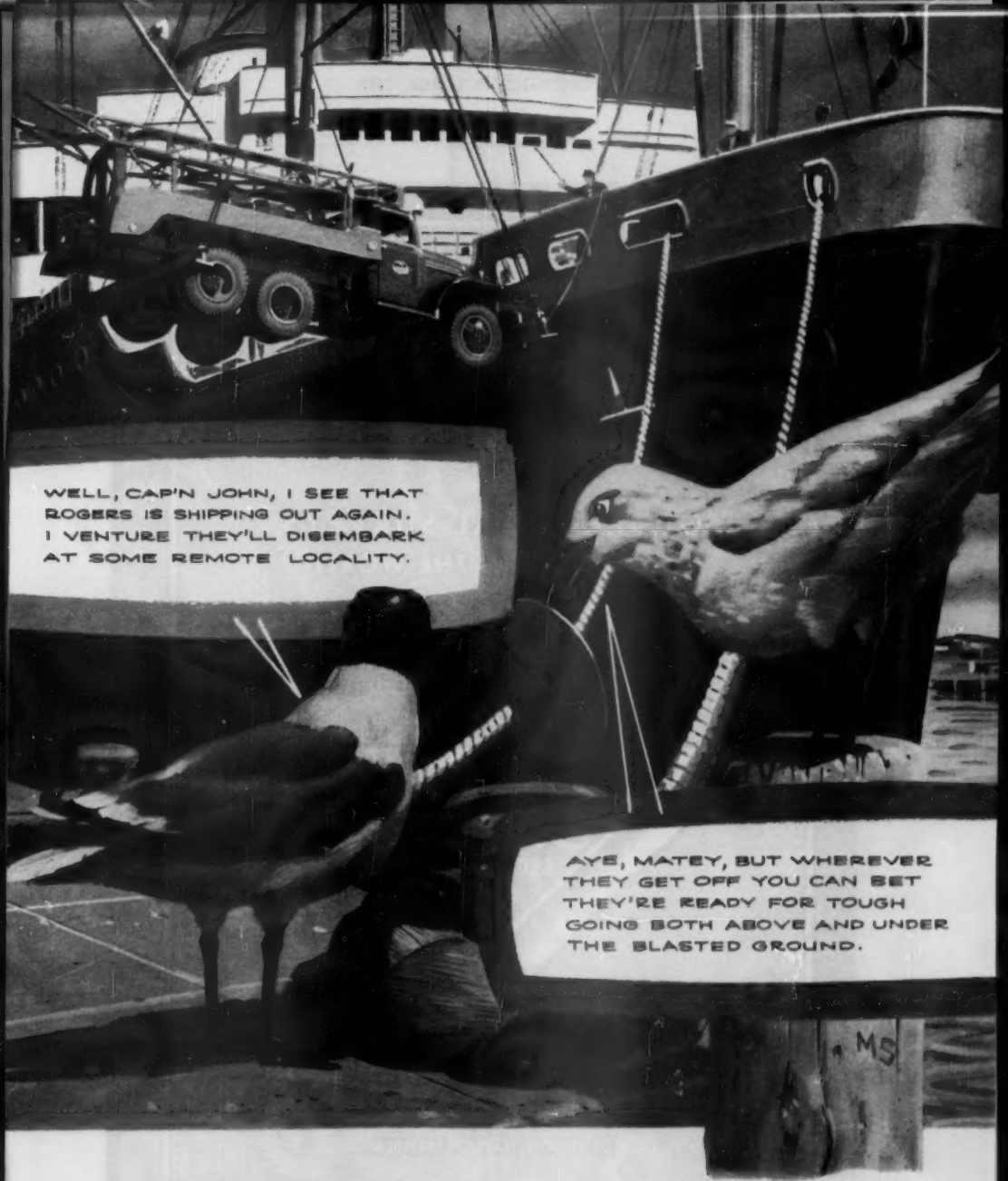
Birmingham, Ala.; Chicago, Ill.; Duluth, Minn.; Hazleton, Pa.; Joplin, Mo.; Los Angeles, Calif.; New York, N. Y.; Pittsburgh, Pa.; Salt Lake City, Utah; San Francisco, Calif.

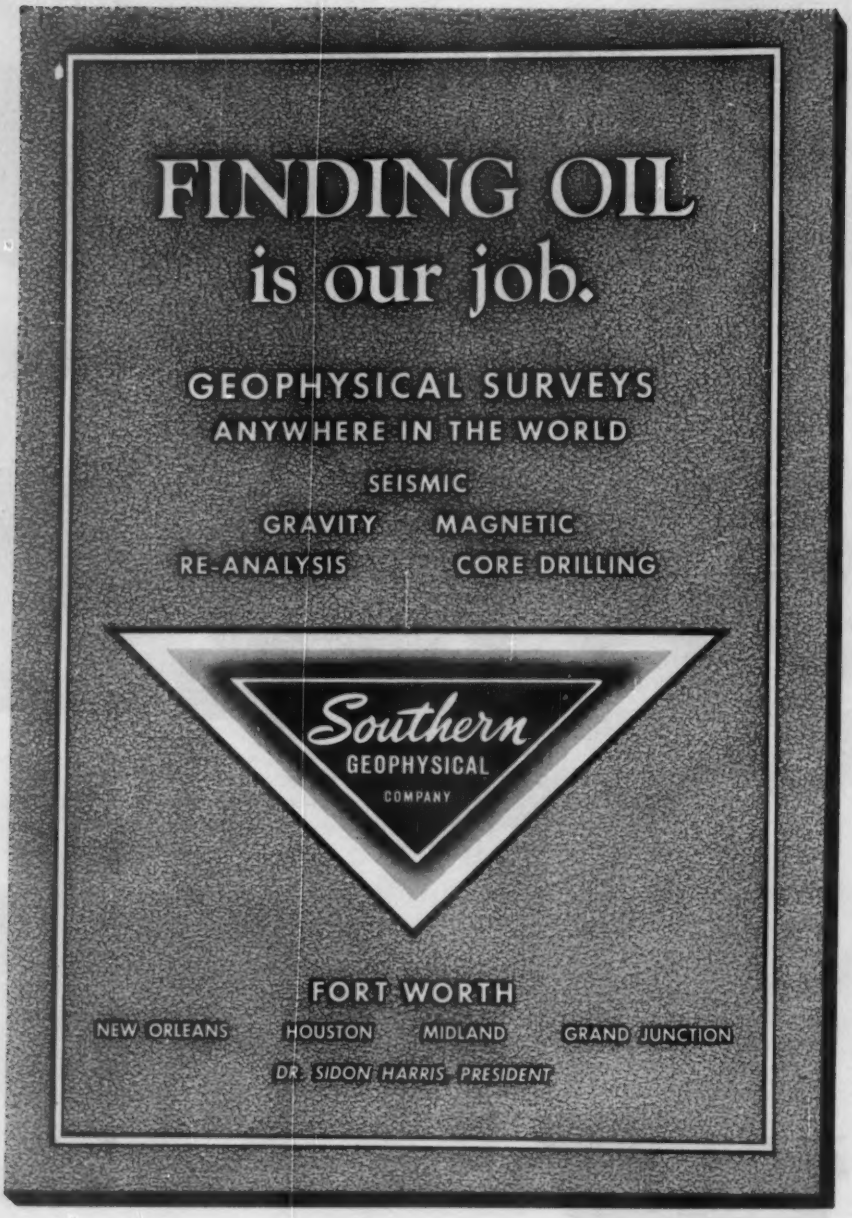

WELL, CAP'N JOHN, I SEE THAT ROGERS IS SHIPPING OUT AGAIN. I VENTURE THEY'LL DISEMBARK AT SOME REMOTE LOCALITY.
AYE, MATEY, BUT WHEREVER THEY GET OFF YOU CAN BET THEY'RE READY FOR TOUGH GOING BOTH ABOVE AND UNDER THE BLASTED GROUND.
MS

Rogers Geophysical Company

3616 WEST ALABAMA • HOUSTON, TEXAS

[redacted] Edificio Republica, Caracas, Venezuela — Mogadiscio, Italian Somaliland — 34 Ave. des Champs Elysees, Paris, France

ROGERS' CREWS GO EVERYWHERE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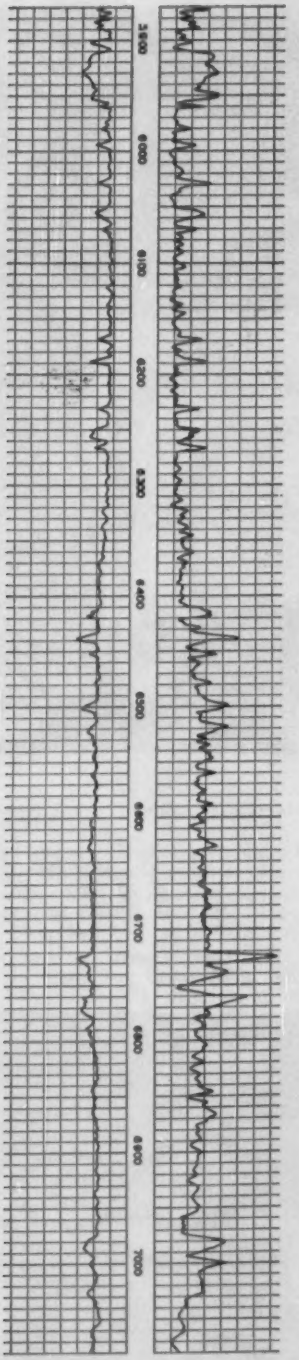

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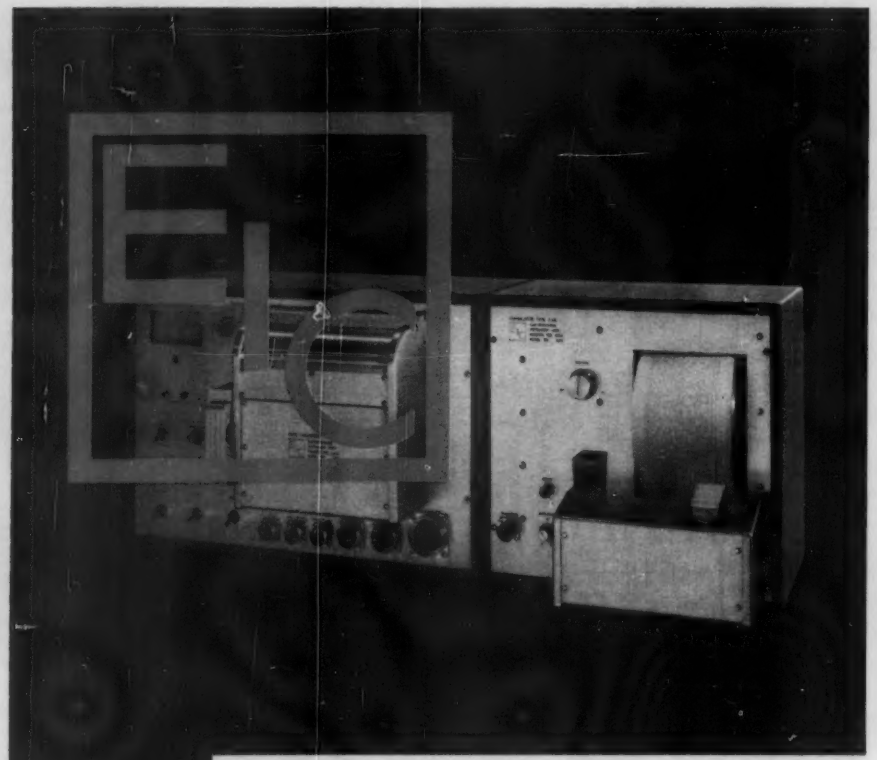


Translator Type T-2A

translates magnetically stored data into permanent visual form without photographic processes.

Developed as an accessory for standard EIC tape recording equipment, the T-2A is adaptable also to other tape instruments.

Providing simple field playback sequentially, the Translator can be coupled electrically or mechanically to the tape transport. More complete laboratory analysis units can be supplied.

Simple and trouble-proof, the T-2A Translator uses a rectilinear penmotor, and can be constructed to almost any specifications.

ELECTRODYNAMIC INSTRUMENT CORPORATION

2508 Tangley Road
Houston 5, Texas

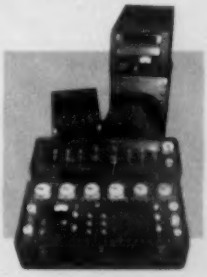
History of the Seismograph
Number 4 in a series.

When seismographs were not so *portable*

About 1900 the design trend in seismographs was toward instruments of ponderous masses, which were thought necessary to obtain the desired pendulum period. One of the most ingenious and beautifully constructed of these heavyweight seismographs was the Wiechert Astatic Pendulum in Germany.

The Wiechert consisted of an inverted pendulum made of cast iron plates formed in a cylindrical shape with a weight of approximately 1000 kg or one ton. This pendulum rested on a universal joint made of thin flat springs, stabilized by the spring connections of its magnifying levers. With this mass of one ton, a period of 12 seconds was obtainable. Two horizontal components are taken off by means of thrust arms at right angles, and you will note the two separate rolls of smoked paper which are the recording medium. The period is regulated by changing the ratio of one of the magnifying levers, which provide magnification on the Wiechert up to 200 times. Although the Wiechert was finely machined, much patience and a delicate touch were required to keep the instrument in adjustment.

Contrasting to the ponderous giants used for earthquake determination, today's exploration seismographs are easily transported in every type of terrain. Most modern and functional of these portable seismographs is the 7000 B system developed by TI which combines three major seismographs in one — VLF Very Low Frequency Refraction Seismograph, 7000 Conventional Reflection Seismograph, and HR High Resolution Reflection Seismograph. Frequency response is 5-500 cps with hundreds of filtering combinations available to obtain the optimum seismograph signals.



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a [redacted] system

7361

the **400th*** **Worden Gravity Meter** *goes into operation!*

* THIS FIGURE EXCEEDS THE TOTAL OF ALL OTHER MAKES OF GRAVITY METERS COMBINED.

Texas Instruments Incorporated is the first and only member of a highly exclusive "400 Club." In the brief span since 1946, 400 compact and dependable Worden Gravity Meters have been precision-manufactured for use in widely varying worldwide services.

In virtually every conceivable operating condition, Wordens have proved their superiority in accuracy, portability, and trouble-free operation. Atop Mount Godwin Austen in Pakistan, in Europe's natural caves, in mine shafts of four continents, on the Greenland Ice Cap, during the IGY in Antarctica, from helicopter, horseback or jeep, from latitudes 0 to 90° . . . both geodetic and exploration Worden Gravity Meters have provided highly valuable information.

The Worden Gravity Meter weighs only five pounds—1/4 to 1/5 the weight of other gravity meters in use. The elastic system of the meter is quartz with basic mass of only five milligrams, and is sealed in a partial vacuum. Internally compensated, no external power source or heating coils are required for operation in any temperature. The Worden Meter does not require pampering or clamping between stations and will maintain its high accuracy under the roughest of expected operating conditions.

For further information on Worden Standard and Geodetic Gravity Meters, write for Bulletin No. GM-204.

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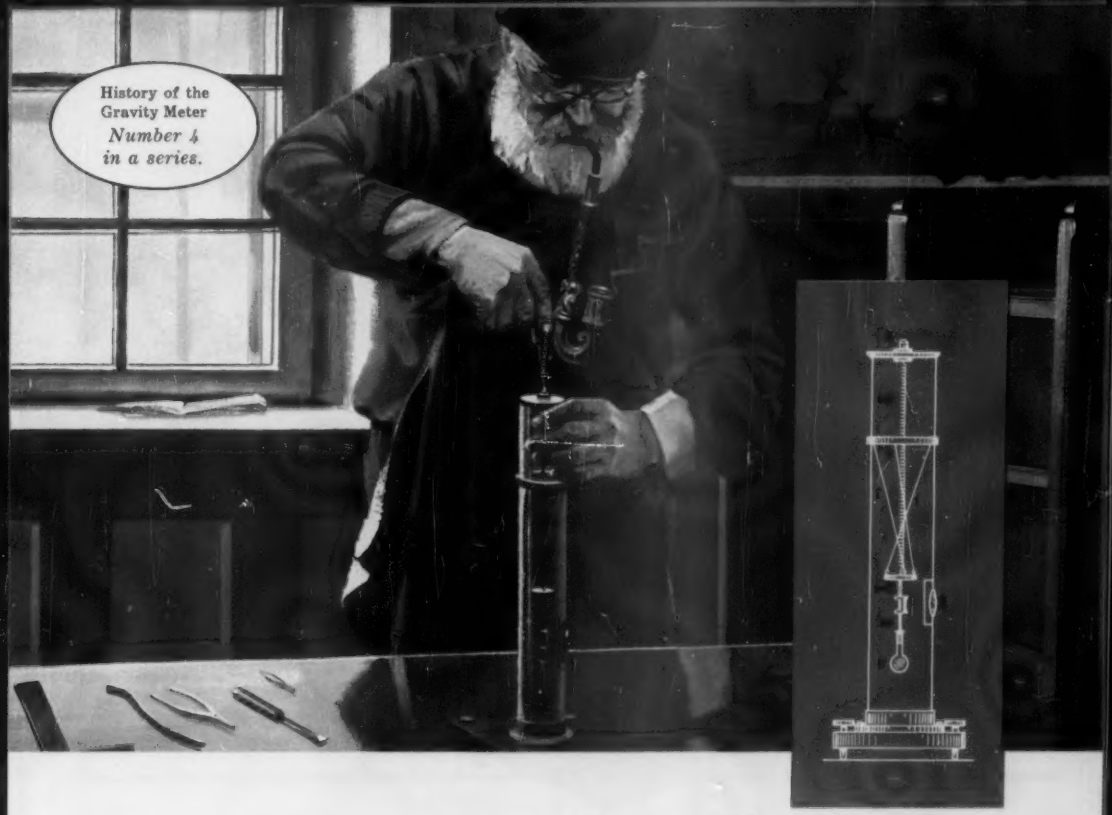
History of the Gravity Meter
Number 4 in a series.



Early development of the *Spring Type* gravity meter

The slowness of the torsion balance and pendulum instruments available provided the incentive for devising a more rapidly manipulated apparatus that could measure gravity directly. In 1833 Sir John Herschel, an English astronomer, first suggested a spring type instrument to be called gravimeter or gravity meter.

Herschel proposed using a spiral spring whose elastic properties were such that a weight of 10,000 grams including its own mass, would produce an elongation of ten inches. The addition of one gram would produce a further extension of 1/10,000 of an inch . . . thus the force of gravity could be measured at any location to within 1/10,000 of its total value. Gauss followed with a bifilar instrument in 1837.

In 1898, A. Schmidt replaced the restituting moment of Gauss' magnet by a helical torsion spring and created the trifilar gravity meter illustrated here. A long spiral spring, sp, is suspended in a glass cylinder. A flask of mercury, p, acts as a pendulum type of mass and is attached to a plate, which in turn is attached at three points with threads, f, to a stationary ring in the cylinder. The plate is oriented by means of a key, k, at the top of the cylinder. The plate attempts to follow this motion, but the torsional forces of the threads are acting in opposition to the turning force of the key. The resultant equilibrium position of both forces is determined by the acceleration of gravity at a particular location. The response to this force is measured optically by the degree of displacement of the mirror, hp, as it deviates from the fixed axis recorded at li. This instrument measured the difference in G only, between respective locations, and was not very reliable because of temperature and hysteresis effects.

Today, the Worden Gravity meter is synonymous with reliability. This rugged, compact and highly accurate instrument, which requires no external power source and internally compensates for temperature changes, is the universal standard for geodetic and exploration surveys.

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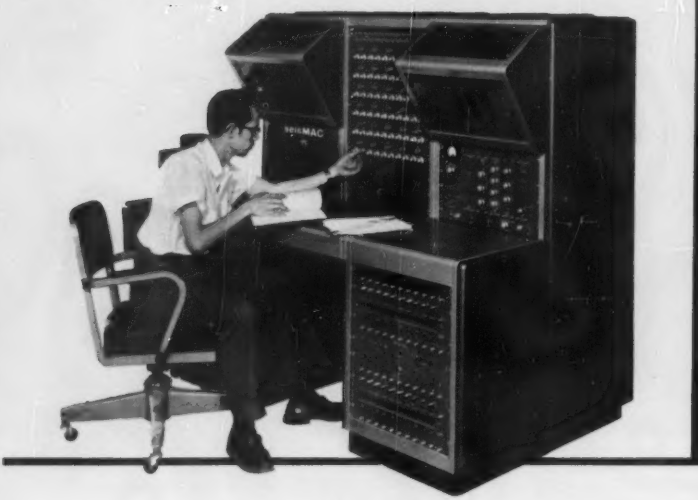

Other components in the TI-equipped Central Processing Office . . .

magneDISC . . . disc-type magnetic recorder

7000B "all purpose" seismograph system

T-Z (time-depth) Camera

The seisMAC, seismic magnetic automatic computer, developed by Texas Instruments Incorporated, is an analog data reduction machine controlled by a digital programmer. seisMAC provides for constant (weathering and elevation) and variable (normal moveout) corrections to be made to any number of seismic traces played back from the magneDISC or other magnetic recorder.

seisMAC, in conjunction with the other individual blocks used in the TI Central Processing Office (or a mixture of equipments, if desired), makes possible the preparation of either time or depth record sections with all the original character of seismic data preserved and the presentation enhanced. Some of the outstanding advantages of seisMAC which permit the presentation of data in its most comprehensible form for final interpretation by the geologist-geophysicist team are:

1. Constant and variable time corrections are made automatically.
2. Unlimited repeatability of data within one millisecond accuracy.
3. Provides 100 millisecond constant plus 100 millisecond variable corrections with no frequency, phase or amplitude distortion.
4. Adaptable with most magnetic transports.
5. Completely automatic during the processing — no adjustments need be made during the operation cycle.
6. No moving heads or cams to become misaligned — seisMAC is the first all-electronic system.
7. Immediate adaptability to any spread or velocity change.
8. Each trace is time-corrected sequentially and independently — no proportioning of a single NMO function for correcting inner traces.
9. Signal remains in analog form with digital programming — high speed processing, accuracy, and repeatability are inherent in the system.

For more complete information on the seisMAC and the TI-equipped Central Processing Office, write for Bulletin No. DS-318.

*TRADEMARK REGISTRATION APPLIED FOR

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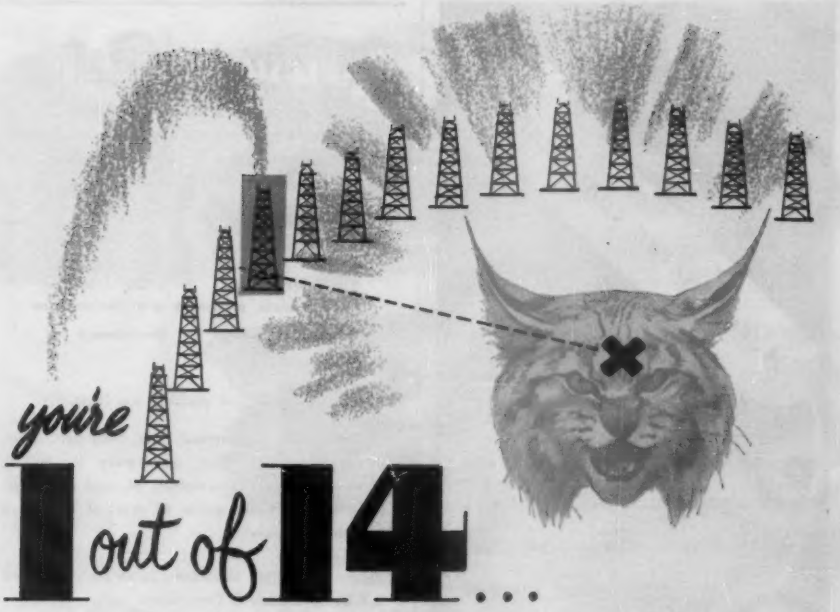

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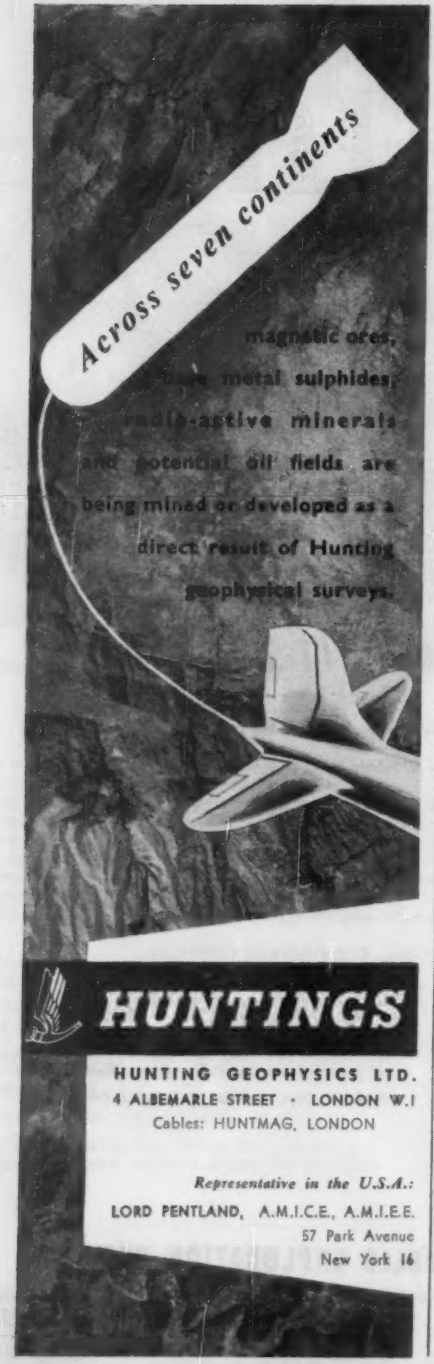

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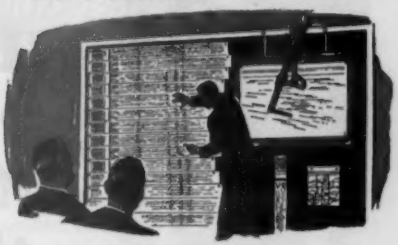

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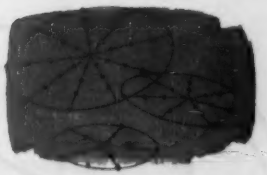

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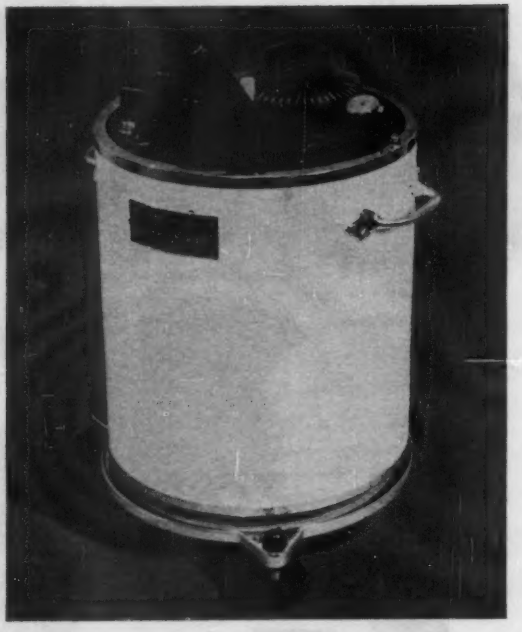

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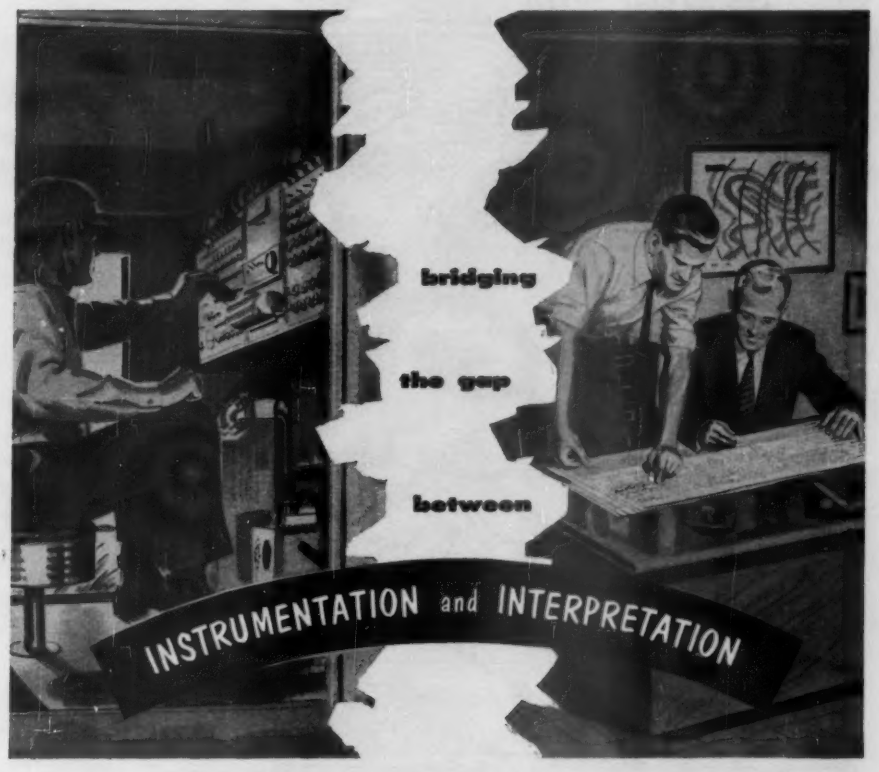

It is a known fact that geophysical instrumentation has advanced faster than geophysical interpretation. Due largely to the competitive efforts of specialized manufacturers, instrumentation has made significant strides in the past ten years. Whereas, interpretation has not kept pace.

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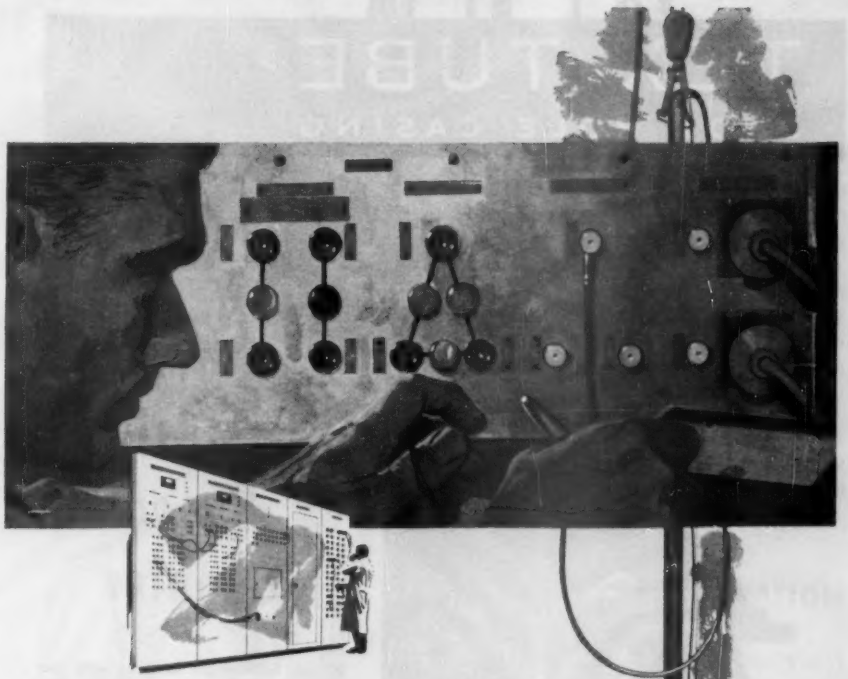

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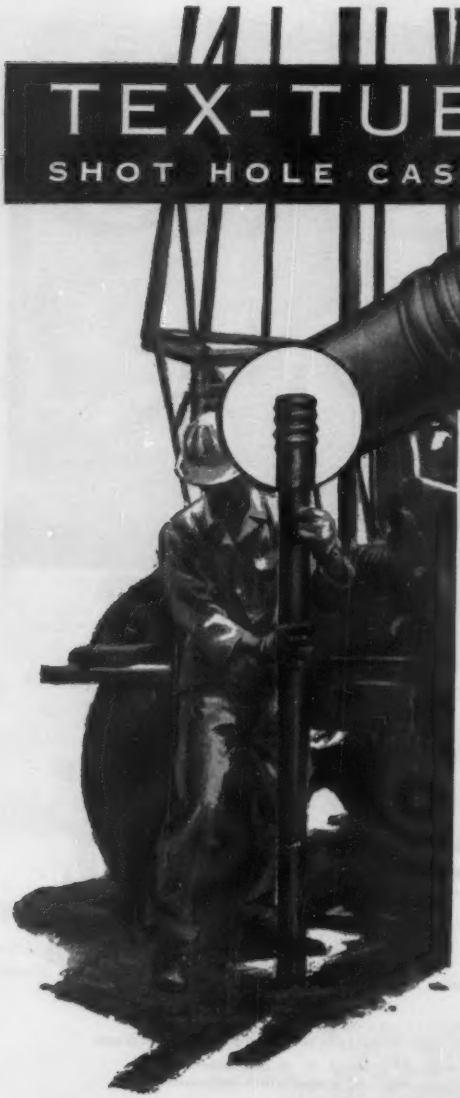

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126—EXTRA PLAY—50% more recording time on the reel! Made with 1 mil polyester backing. .35 mil coating of high potency oxide. Offers improved high frequency response, improved short wave length output, and better head conformity eliminates signal loss.

146—LONG WEAR—Rugged newcomer! This premium tape gives you 3.5 db greater output at short wave lengths, yet withstands heat-wear in temperatures up to 200°F. and eliminates head build-up. Has 1.5 mil polyester backing, .35 mil coating of "High Output" long wear oxide.

149—LONG WEAR, EXTRA PLAY—Matches 146 for heat-wear resistance and magnetic properties but records 50% longer because of its thinner 1 mil polyester backing. Selection for use of this tape should be based on strength versus playing time as the determining factor.

Choose from a complete line of "Scotch" Brand Instrumentation Tapes for industry and defense

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FREE BOOKLET gives you specific engineering data on dropouts plus complete physical and magnetic specifications of these famous "SCOTCH" Brand products. Write: Minnesota Mining and Mfg. Co., Dept. LO-107, St. Paul 6, Minnesota.

*Measured by recording 200 non-return pulses per inch on a 0.035" track. A reduction to less than 90% normal signal amplitude constitutes a signal error. Zero errors are measured by saturating the tape unidirectionally. Each spurious signal greater than 10% of normal signal amplitude constitutes a zero error. Errors per roll based on recording 7 tracks on rolls ½" x 2500'.
**Based on a 8750 cps signal played at 7.5 ips.

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WHICH MAGNETIC TAPES ARE BEST FOR YOUR INSTRUMENTATION NEEDS?

Tape Number and Description	Stability	Strength	High Temperature Performance	High Speed Performance	Long Wave Length Output	Short Wave Length Output	Recording Time
108 General Purpose	Best	Best	Good	Good	Good	Good	Normal
109 General Purpose	Good	Good	Good	Good	Good	Good	Normal
128 High Output	Best	Best	Very Good	Very Good	Best	Good	Normal
148 Long Wear	Best	Best	Best	Best	Good	Best	Normal
149 Long Wear Extra Play	Best	Good	Best	Best	Good	Best	Extended
159 Extra Play	Best	Good	Good	Good	Good	Best	Extended

All quantities expressed are relative to No. 109

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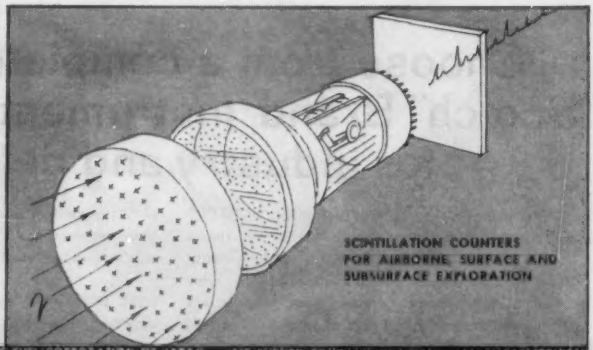

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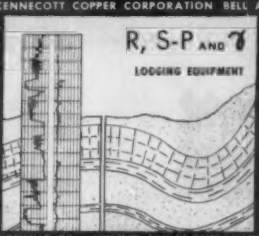

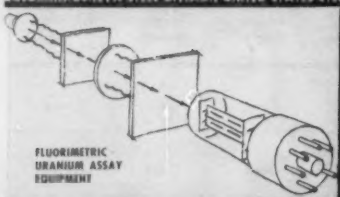

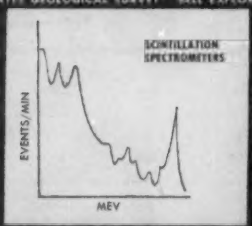

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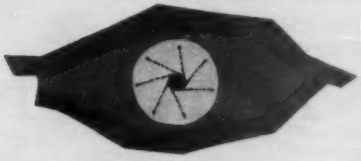

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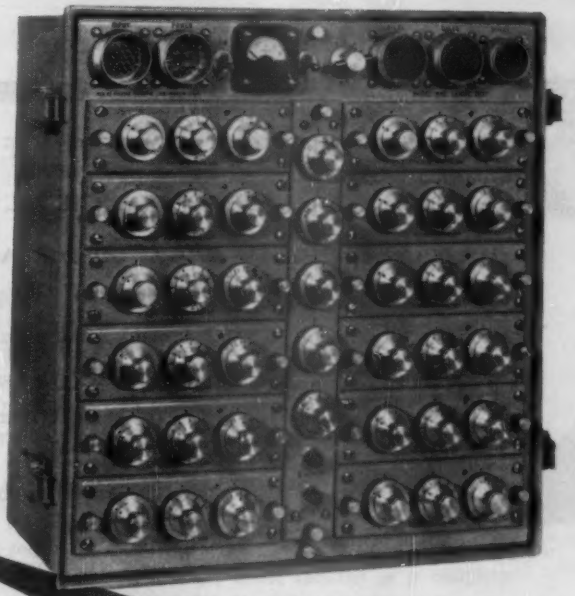

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- **automatic filter switching**

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- **improved signal handling capacity**

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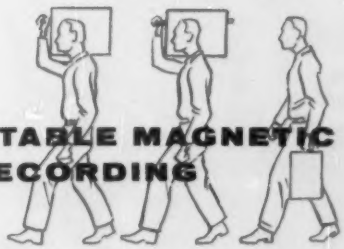
SIE

MAGNETIC RECORDING and ANALYSIS SYSTEMS

Here are some highlights from the SIE magnetic recording and analysis equipment program. To date, SIE has originated and is producing the most complete line of inter-related recording systems, tape transport devices, and data processing equipment available. Ranging from the compact PMR-7 Portable Magnetic Recorder for Direct Recording to the versatile MS-12 **GeoData** System, SIE magnetic instruments are designed to permit maximum flexibility in the choice of recording and analysis systems "tailor made" for the application. This program eliminates the purchase of equipment more elaborate than is necessary, and at the same time permits the addition of more complex recording and analysis instruments as required.

Whether your application requires a simple direct recorder or a complete office analysis system, be sure to contact SIE for full information when you plan your magnetic tape instrumentation program.



PMR-7 PORTABLE MAGNETIC DIRECT RECORDING SYSTEM

Three men can carry the complete PMR-7 Portable Direct Recording System including the 28 channel recorder, the PDA-2 Amplifier Unit, and the Power Supply. The recorder is available with fixed or movable head assemblies, and the records can be played back on an SIE Recorder or analysis system.

Designed for rough field duty, the PMR-7 utilizes magnesium and fibreglas construction for maximum strength in combination with light weight. Hermetic sealing of critical components, and water-tight case construction prevents moisture penetration even after submersion.

Judged by the toughest standards for field equipment: strength, durability and light weight; and meeting the famous SIE standards for recording accuracy and ease of operation, the PMR-7 meets every requirement of a modern seismic program.

SIE

MAGNETIC RECORD ANALYSIS SYSTEMS

SIE manufactures office playback and magnetic record analysis systems to cover a wide range of applications. Among the tape-transport systems used in these applications are the MR-5 twin-drum recorder and the MR-7 and MR-9 three-drum recorders. The design program behind these instruments has been planned to provide units which can be used separately or in groups depending on the application. This policy permits continuous development of new equipment which can be used with previous units, and enables users of SIE instruments to maintain greater flexibility in organizing their data processing equipment investment programs.

The MS-12 GeoData System, the most elaborate of these systems, provides time cross-sections, and normal moveout and weathering-elevation corrections, in addition to many other interpreting operations. Other Recorders and interpreting equipment are combined for office or field playback. Contact SIE for full information regarding these instruments and how they can be combined to provide a custom designed installation to meet all of your analysis equipment requirements.

SIE

GeoData

SYSTEM

MODEL MS-12

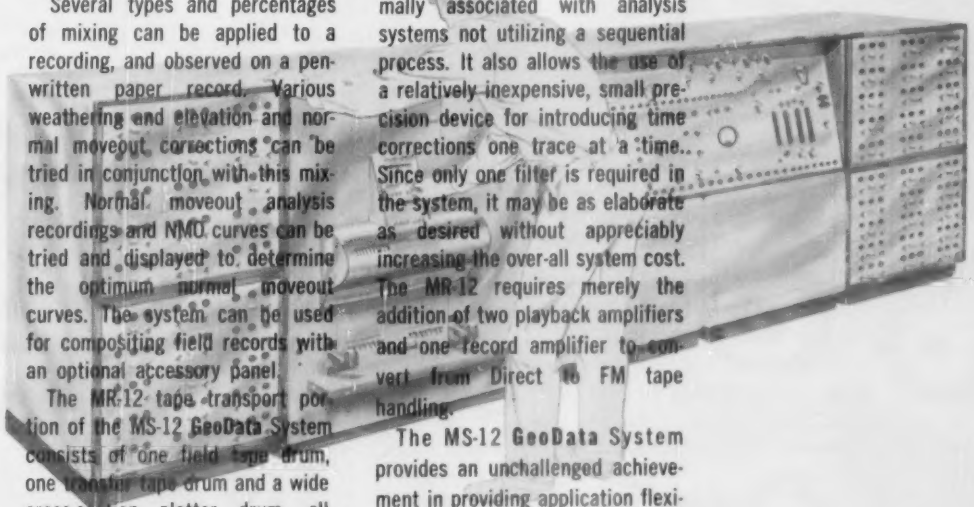
The MS-12 **GeoData** System processes FM and Direct recordings. It provides a record cross-section which is pen-recorded on paper and can be photographically reproduced. Cross-sections can be isopached or set to a desired reference plane. The graphically presented information is also permanently stored on magnetic records.

Magnetic or visual records which have been trace-mixed, filtered, corrected for weathering, elevation, and normal moveout can be made with **GeoData** equipment. Filter analysis may be made of field records by playing the same record back through several filters and displaying it as a pen-written paper recording.

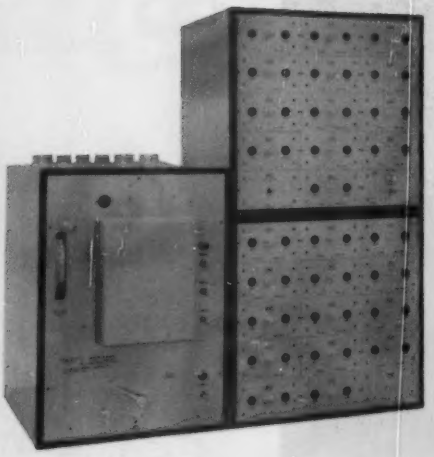
Several types and percentages of mixing can be applied to a recording, and observed on a pen-written paper record. Various weathering and elevation and normal moveout corrections can be tried in conjunction with this mixing. Normal moveout analysis recordings and NMO curves can be tried and displayed to determine the optimum normal moveout curves. The system can be used for compositing field records with an optional accessory panel.

The MR-12 tape transport portion of the MS-12 **GeoData** System consists of one field tape drum, one transfer tape drum and a wide cross-section plotter drum, all mounted on a common-driven shaft. The two standard SIE magnetic drums have adjustable combination FM and Direct recording head banks. The third drum is a 24-in. oscillographic drum for pen recording. Two galvanometer pen writers are provided for this visual display unit. One of these pens utilizes 2" of the oscillographic drum for monitoring purposes to observe time break, 100 cps reference signal and other information. The second galvanometer pen is used to display signal channels. The pen movement is adjustable to provide any desired horizontal scale for making cross sections.

The system is entirely sequential in operation in that it transcribes one trace at a time from the field tape, to either the transfer drum or the paper drum. This eliminates most of the many electronic amplifiers which are normally associated with analysis systems not utilizing a sequential process. It also allows the use of a relatively inexpensive, small precision device for introducing time corrections one trace at a time. Since only one filter is required in the system, it may be as elaborate as desired without appreciably increasing the over-all system cost. The MR-12 requires merely the addition of two playback amplifiers and one record amplifier to convert from Direct to FM tape handling.



The MS-12 **GeoData** System provides an unchallenged achievement in providing application flexibility for every interpretation and analysis program. For full details, contact SIE or your nearest representative.



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The MR-4 and MR-8 are only two of the SIE magnetic recording systems available for every application in the field or office. Today, more than 60 complete SIE magnetic systems are in operation and have established the Standard of the Industry in magnetic instrumentation.

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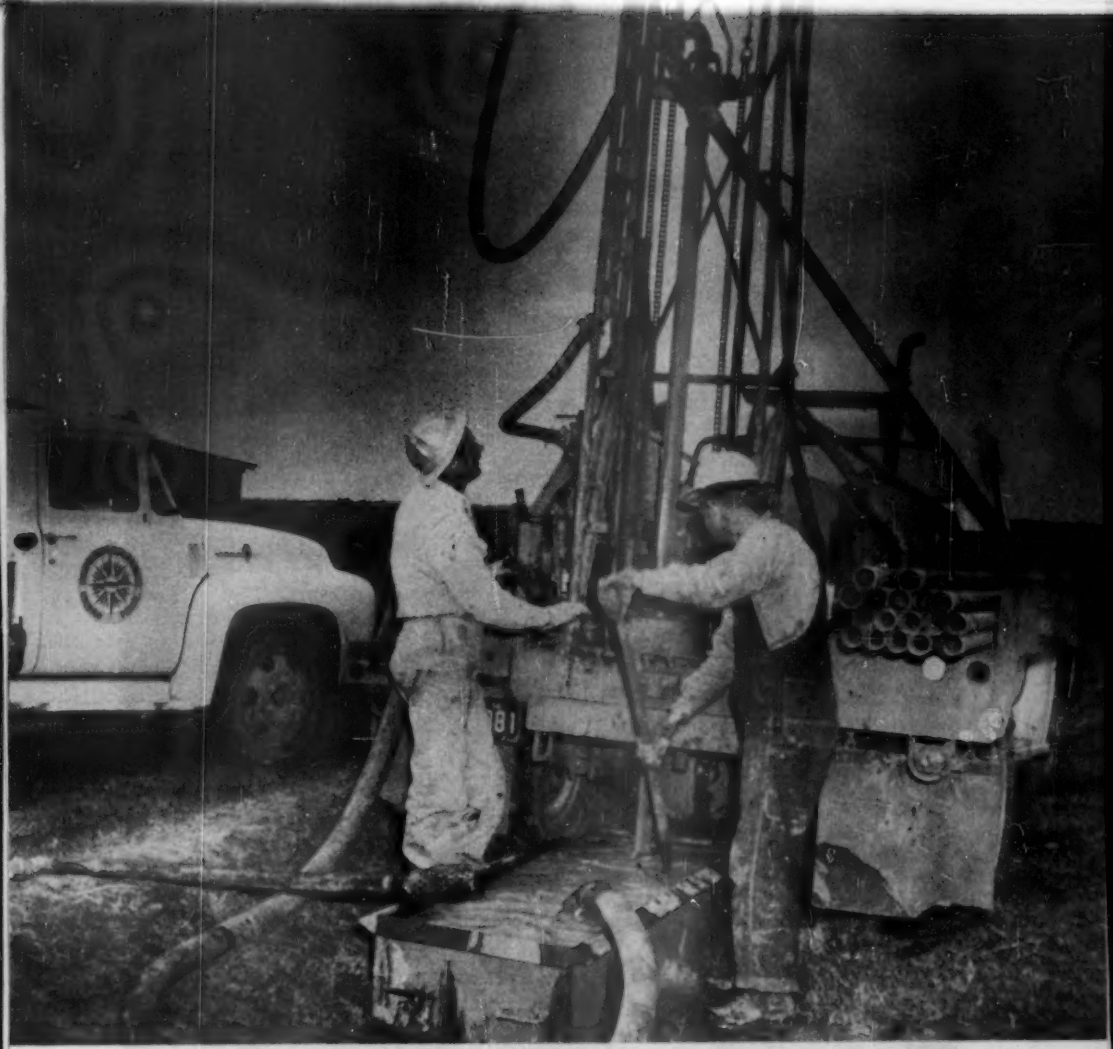

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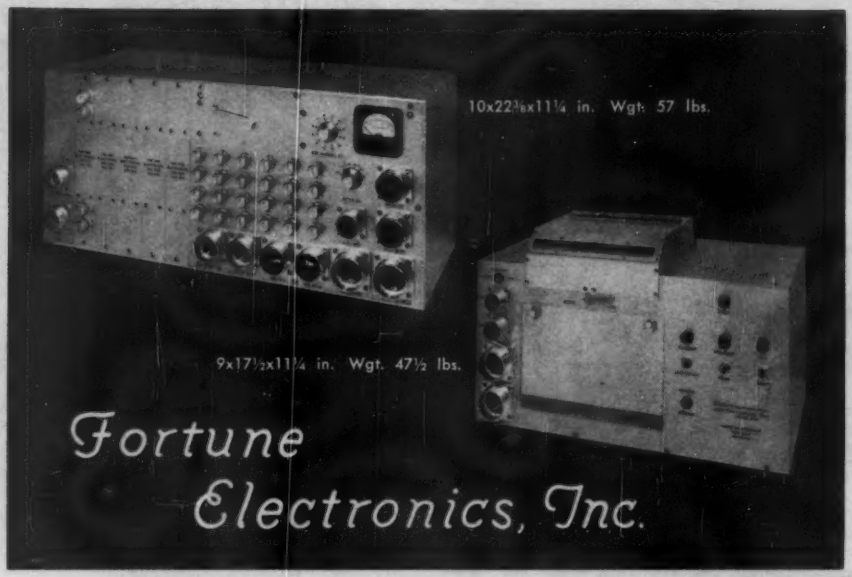

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The SR-3 Direct Recorder is a light weight, magnetic recorder which offers improved transient and steady state response. Advanced head design makes possible the SR-3's high standard in fidelity of reproduction of seismic data.

Rugged and compact, the SR-3 meets the most exacting requirements under the toughest field conditions. Precision parts and expert craftsmanship are employed in the construction of the SR-3 resulting in superior performance of both the electrical and mechanical elements.

To insure greater accuracy, particular attention has been given the drive and timing systems. A frequency standard, especially designed by Riverbank Laboratories for Fortune Electronics, controls the drive motor speed and serves as the timing reference.

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Physical Characteristics

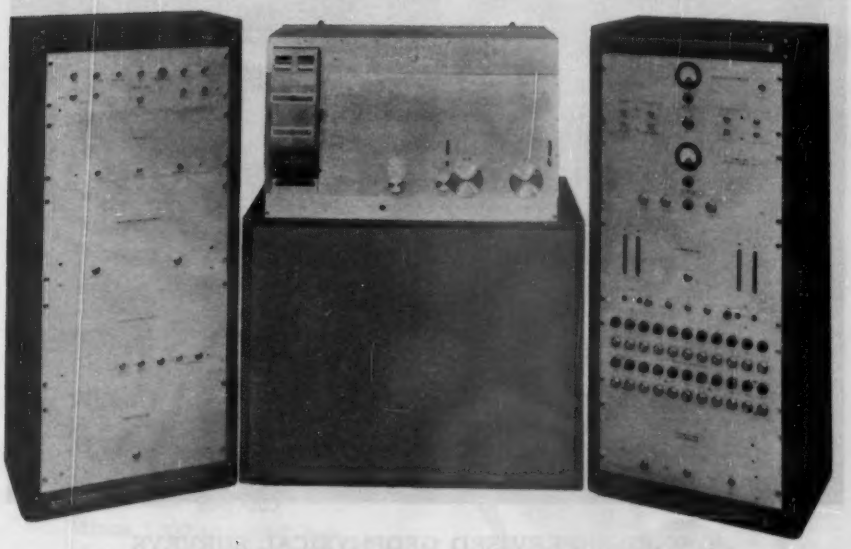
Tape Transport	7.5" Dia. Drum
Number of Channels	24 Seismic 4 Auxiliary
Track Width	.060"
Track Spacing	¼" Center to Center
Record Length	6 Sec. (6.6 Sec. Drum Rev.)
Drive	50 Cycle Hysteresis Motor Gear Coupled to Drum
Tape Speed	3.6" per Sec.
Head Adjustment	± 100 ms

Electrical Characteristics

Signal/Noise Ratio	50 db RMS to RMS
Total Harmonic Distortion	2½% @ 100% Rec. Level
Frequency Response	5-500 cps
Crossfeed	—40 db @ 10 cps
Timing Accuracy	± 1 ms
Power Requirements	17 Amp. @ 12 V

MTC-1 OFFICE PLAYBACK SYSTEM

- A versatile, simple to operate machine, the MTC-1 processes data from three drum type systems.
- A playback of all channels is made simultaneously.
- Sequential cross section plotter optional.
- A sequential corrector system transfers information from field tape to final tape through an intermediate corrector drum. Operation is automatic. No manual adjustments are necessary during transfer.
- Static corrections may be made either in transfer or playback process.



For Complete Information on the MTC-1 Office Playback System Contact—

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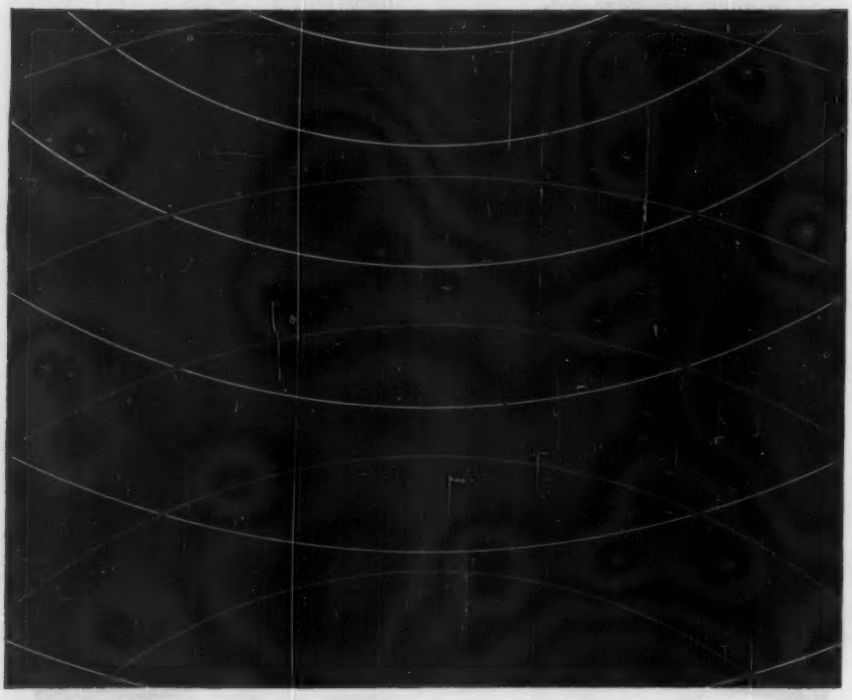

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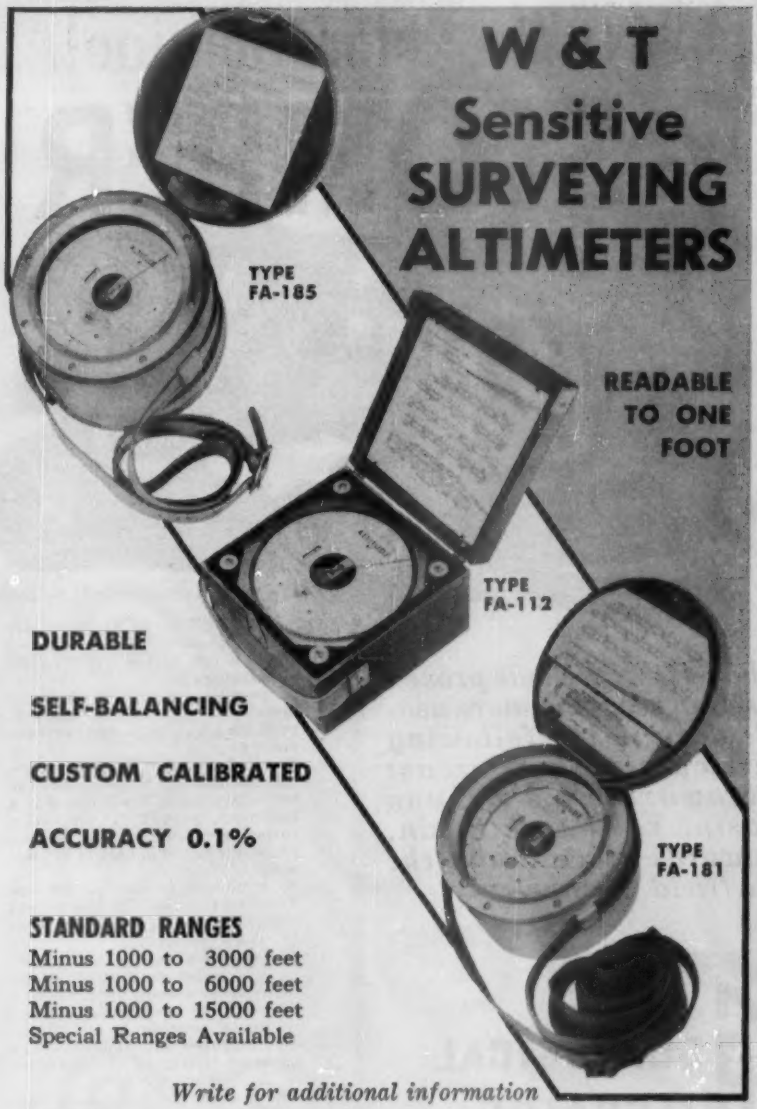

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The STOMPER has proved itself in securing more usable data in the following difficult record areas: Delaware Basin, Juno Basin, Val Verde Basin, Edwards Plateau and the Sheffield Channel.

The STOMPER is an exclusive design of Geophysical Integrators, Inc. Here are a few of the STOMPER'S many advantages:

1. It permits the use of a much larger seismic weight (approx. 9000-lbs.) and hence more seismic energy.
2. The G. I. Stomper has no springs, and no external moment and the secondary noises are reduced to a minimum, permitting an undisturbed recording of the seismogram due to the impact of seismic weight.
3. A bulldozer is carried on the Tournapull tractor of the weight vehicle for use in improving trails in rough terrain.
4. The road clearance of the Stomper is 15½ inches, permitting its use in rocky or stumpy land where a conventional low clearance truck would be severely handicapped.
5. An improved method for very accurate timing of the initiation of the seismic wave.
6. The size of the Stomper is such that a 9000-lb. weight is considered to be a small fraction of its normal full-loaded condition, affording trouble-free operation and resulting in more productive hours per month.

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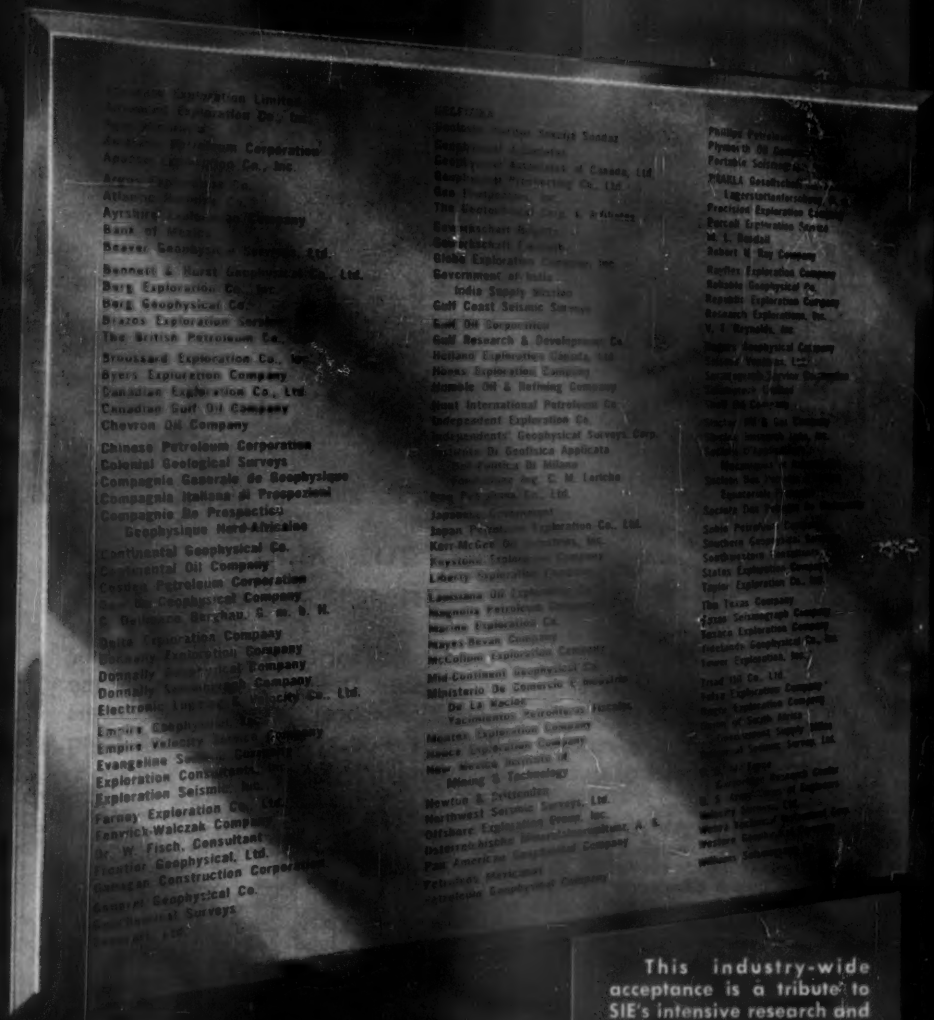

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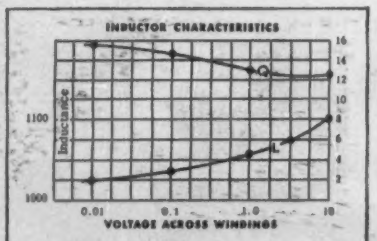

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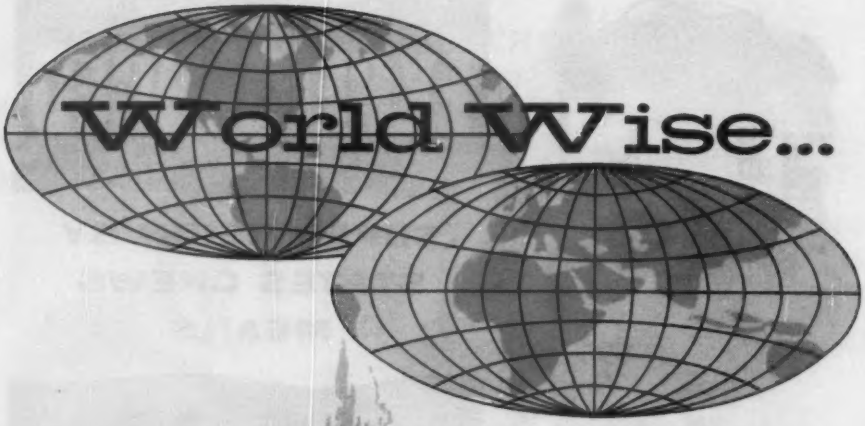

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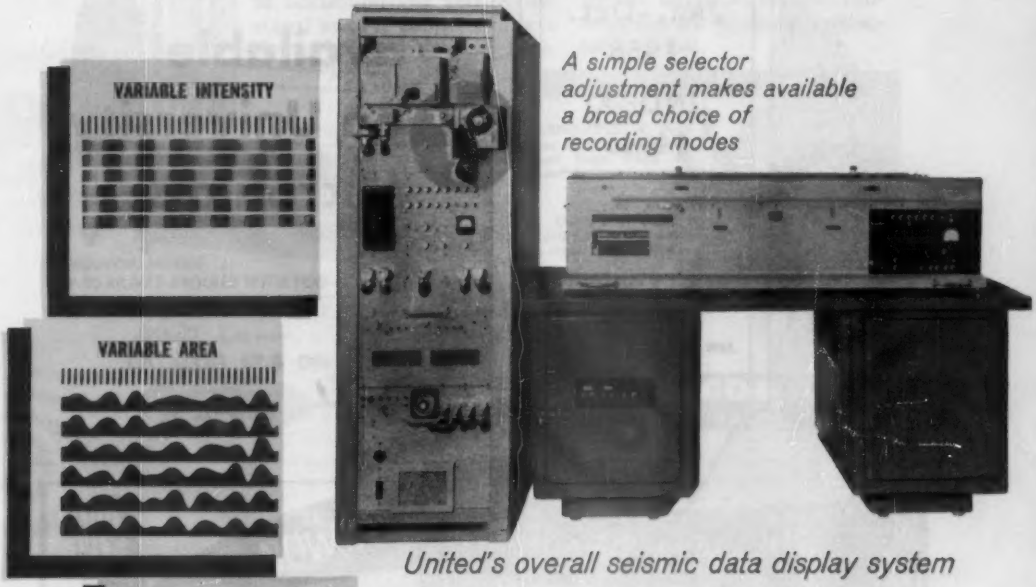

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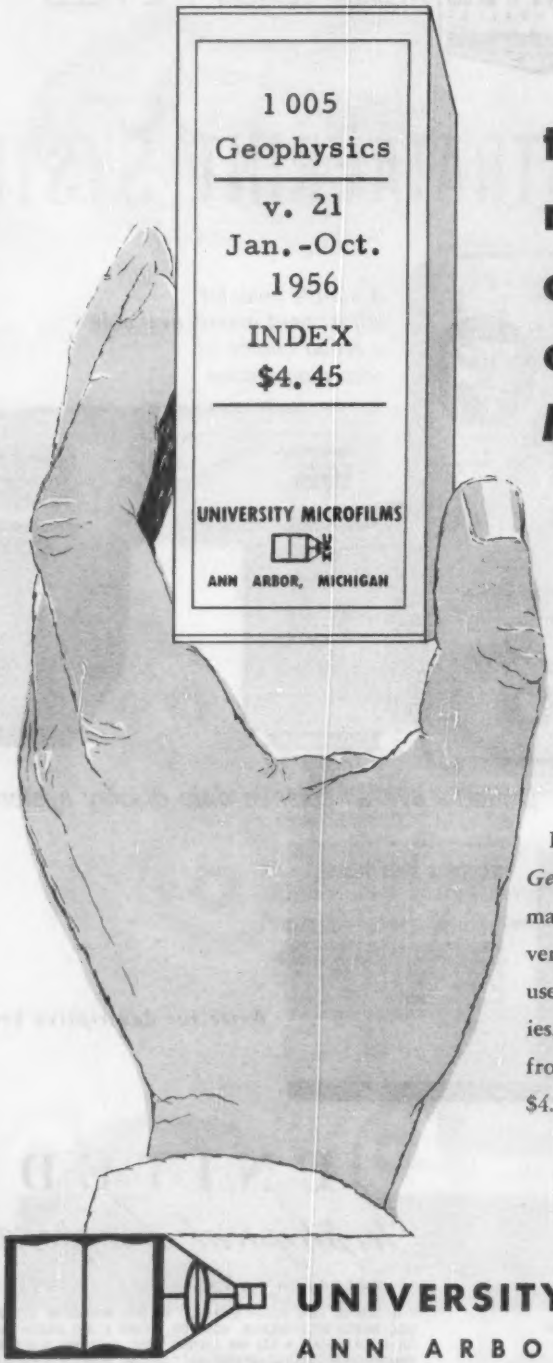

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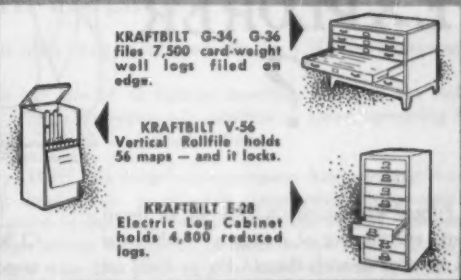
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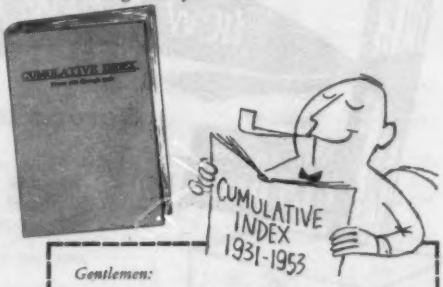
Filbert stared blankly into space. A dull film clouded his eyes. Surely, with luck, he would be dead in five minutes. But visions of his widowed wife and fatherless children pulled him to his feet and sent him trudging out the door . . to the library.

It would take all day. He'd be spending valuable time his company could hardly afford. And he'd be using all his exploration skill to locate that blessed paper — not to mention structures . . . Filbert stopped at a drug store and bought $4.00 worth of aspirin.

Had Filbert spent that $4.00* on the CUMULATIVE INDEX, he would have saved himself that headache and many, many more. The S.E.G. CUMULATIVE INDEX 1931-1953 is a complete library on geophysical data at the tips of your fingers. Remember, a man is as useful as the knowledge he possesses. The CUMULATIVE INDEX is knowledge on your desk!



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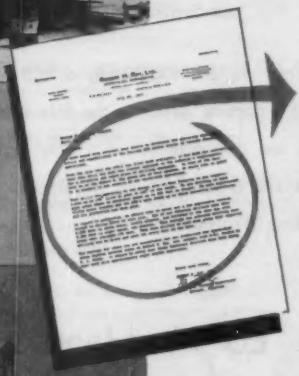

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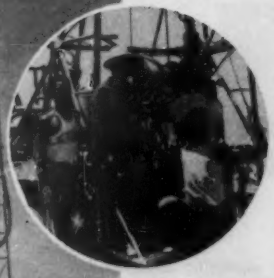
In regard to production, we should like to point out a few impressive records turned in during March of this year. One of our Pakistan drillers went down 2,028 feet in seven hours, twenty minutes, and followed it the next day with 2,256 feet in eight hours, ten minutes. This footage was achieved drilling shot holes that avereged 170 feet. They were drilled in sand dune areas that required drilling mud be mixed and used for every foot of the hole.

The footage for these two are exceptional but our production has approached these figures several times on Robert H. Ray, Ltd. seismic crew S-93, headed by E. J. Glenn. It should be noted that these Pakistani drillers have been doing this work with approximately eight months experience.

Yours very truly,
ROBERT H. RAY, LTD.
Gordon D. Causey, Supervisor
Karachi, Pakistan



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OR
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Activity in the Edwards Plateau and the Val Verde Basin has led us into a sort of *specializing* in getting along with the land owners and stockmen in that area.

Having had an office in San Angelo for some five years, and parties in the surrounding towns practically continuously, we have become personally acquainted with the land owners as well as with *their* problems. In short, getting permits is our specialty.

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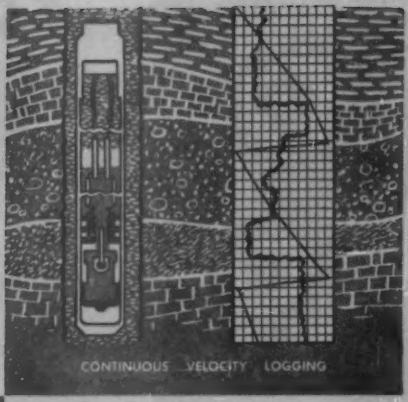

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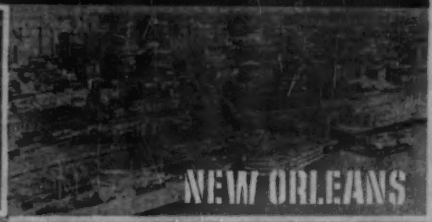

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